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A REVISION OF ROWLAND'S SYSTEM OF WAVE-LENGTHS.

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1. ROWLAND'S system of wave-lengths has become the basis of all spectroscopic measurements made in recent years, and with the progressive increase in the precision of these measures the necessity has now arisen of testing the reliability of that important basis, and, in case it should not appear as adequate, of correcting it by new series of observations in order thus to create a foundation sufficient for all demands.

Aside from the earlier and provisional publications of Rowland, his system of wave-lengths as at present accepted appears in three different forms:

a) The standard wave-lengths in the solar spectrum, and

b) The standard wave-lengths in the arc spectra of different metals which was first published in *Astronomy and Astro-Physics* (**12**, 321, 1893) under the title "A New Table of Standard Wave-Lengths." For brevity I shall denote the wave-lengths of these two series by ⊙ St. and M. St. Rowland gave in 1896 in the *Memoirs of the American Academy of Arts and Sciences* (**12**, No. 2, 101) a more extended account of the origin of these standards.

c) The measurement of the whole solar spectrum which appeared in the ASTROPHYSICAL JOURNAL, Volumes 1 to 5, in the years 1895–97, under the title "Preliminary Table of Solar Spectrum Wave-Lengths." The wave-lengths in this table I shall designate by P. T.

The question which first arises, as to how far these three series of wave-lengths are to be regarded as coincident, so that we can speak of a single Rowland system, may be answered in two different ways—first, on the basis of the history of the development of these series, and secondly, by a numerical comparison of them.

2. The history of the development of Rowland's wave-lengths is briefly as follows. By taking the mean of the absolute measures of Ångström, Müller and Kempf, Kurlbaum, Peirce, and Bell, Rowland derived for the Fraunhofer line D_1 the wave-length

$$\lambda = 5896.156.$$

To this line he connected thirteen further "primary standards" (P. St.) in the visible spectrum by visual measures of coincidences with the use of several concave gratings of 21½ feet focus. These P. St. are single lines in only certain instances; being for the most part mean values from the wave-lengths of groups of two, three, and four lines, which are separated by distances as great as 76 tenth-meters. As the result of numerous measurements he obtained twenty-six equations of condition of the form

$$nA - mB = D,$$

where n and m represent the order of the coinciding spectra concerned, B the wave-lengths of the observed lines, and D the separation of the lines measured with the eyepiece micrometer. The measured distances of the lines observed as coincident are in part very large: only in eight cases are they smaller than ten revolutions of a screw for which one revolution = one tenth-meter in the first order of the grating concerned; in eleven cases it is more than twenty revolutions, and in two cases it even exceeds one hundred revolutions. Although the micrometer screw employed by Rowland, which he himself made in the most careful manner

and investigated, is undoubtedly of the highest excellence, there is nevertheless a certain danger in the measurement of such long distances, particularly as these distances frequently could be measured only on one side, so that it was not possible to interpolate the lines of the one order *between* those of the other order. How Rowland obtained the screw-value with sufficient accuracy for such long distances is not to be readily ascertained from his publications, which, indeed, contain so few data as to the measurements themselves that a test of them is impossible.

3. Rowland did not solve the twenty-six equations of condition for the wave-lengths of the fourteen P. St. by the method of least squares, although this would have been quite simple, as each equation contains only two unknowns with integral coefficients ranging from two to seven. He employed *per contra* the process of successive approximations, which had the advantage of greater clearness, and without doubt also led to a system of values which satisfied very well the equations of condition.

From this process of adjustment Rowland deduced for the line D_1 the wave-length 5896.160, and, in order to bring this value into better agreement with the above-mentioned mean from the absolute measurement, he reduced[1] all the wave-lengths found in the solution by $\frac{1}{200,000}$. In this way he now obtained for D_1, $\lambda = 5896.157$.

The P. St. determined in this way lie between the limits λ 4215.6 and λ 7040.1. Subsequently the Fraunhofer line A was also once connected in the spectrum of the first order with the nearest normal in the second order, for which purpose it was necessary to measure with the screw over a distance of 84 tenth-meters; a further connection was also obtained by the coincidence of the second and third order.

4. The 798 ⊙ St. and the 404 M. St. were now connected with these 15 P. St. as follows: The visual portion of the solar

[1] The corrections actually applied by Rowland (*loc. cit.*, p. 139) do not agree with this statement in the case of several of the standards. It cannot be ascertained whether this is due to typographical errors, of which the publication unfortunately contains a very large number, or are errors of computation, or whether certain of the standards were intentionally further altered for some reason which was not given.

spectrum between λ 4048 and λ 7714 was repeatedly measured with a micrometer screw 5 inches long, with the use of various gratings. The portions separately measured with the screw were then united by means of the overlapping portions into thirteen long strips, which rendered possible not only an interpolation of the standards, but also an adjustment of the P. St.

Eighteen photographs were made with the solar spectrum of one order situated between two strips of the solar spectrum of another order for the continuation of the work into the ultra-violet region. A large number of plates was also made which contained a solar spectrum and beside it metallic spectra of different orders. The measurement of all these plates, which was carried on by Mr. Jewell, now produced numerous combinations between the different parts of the spectrum, and thus there always occurred, along with the interpolation of the standards, also an adjustment of the P. St. Thus for each wave-length of the standards there were developed a number of individual determinations from which finally the mean was taken; these are the numbers published as ⊙ St. and M. St.

5. It follows from this origin that the whole system of ⊙ St. is entirely coincident with that of the P. St., but that the wave-lengths of the single lines in the two systems may differ by small quantities from each other. Thus the line D_1 appears under the ⊙ St. with the wave-length

$$\lambda = 5896.154.$$

The ⊙ St. are to be regarded in every case as the better adjusted system in comparison with the P. St.

6. The conditions are less simple with the M. St. Rowland remarks[1] as follows:

> In every plate having a solar and metallic spectrum upon it, there is often — indeed, always — a slight displacement. This is due either to some slight displacement of the apparatus in changing from one spectrum to the other, or to the fact that the solar and the electric light pass through the slit and fall on the grating differently. In all cases an attempt was made to eliminate it by exposing on the solar spectrum both before and after the arc, but there still remained a displacement of 0.01 to 0.02 division of Ångström, which was determined and corrected for by measuring the difference between

[1] *Memoirs of the American Academy*, **12**, 116.

the metallic and coinciding solar lines, relating a great number of them, if possible.

It follows from this remark that the wave-lengths of the M. St. which were directly measured and hence accurately referred to the system of the ⊙ St., in case the apparatus was in order, were subsequently so altered by empirical corrections, now larger and again smaller, that as accurate a coincidence as possible was attained between the lines of the arc and the solar spectrum.

Jewell was the first to call attention to the erroneousness of this process, in his very valuable paper on "The Coincidence of Solar and Metallic Lines."[1] It cannot now be ascertained by what amounts the individual M. St. were falsified by the application of these corrections. More definite information could not be given to me by Mr. Jewell in response to a letter which I addressed to him several years ago. We must therefore first remember that all the M. St. are erroneous by small amounts, which cannot be recomputed, lying in the vicinity of 0.01 to 0.02 tenth-meters, and in general too large relatively to the system of the ⊙ St. In certain parts of the spectrum the ⊙ St. may be affected to a small amount by the application of these empirical corrections, since Rowland repeatedly also employed the M. St. in order to derive the ⊙ St. in a spectrum of another order by the method of coincidences.

7. While the progression of the errors which arose from the application of these corrections is very gradual, so that the error for neighboring lines is always of nearly the same amount, I must now call attention to another source of error which may have produced larger deviations of *individual* lines. As already mentioned, the ⊙ St. and the M. St. are mean values from a number of different sorts of determinations; and the number of plates employed is very different for each line. The following series of M. St. in the iron spectrum may serve as an example.

Even this short list shows that the M. St. measured on eight or nine plates either coincide very closely with the ⊙ St. or fall on the negative side of them, while all the lines measured only once or twice deviate, in some cases by very considerable

[1] ASTROPHYSICAL JOURNAL, 3, 89, 1896.

TABLE I.

M. St.	No. of Measures	⊙ St.	M. St.−⊙ St.
4308.072	8	.071	+ 1
4325.932	8	.940	− 8
4352.908	1	.903	+ 5
4369.948	1	.943	+ 5
4376.108	1	.103	+ 5
4383.721	9	.721	0
4404.928	9	.927	+ 1
4415.298	8	.299	− 1
4447.912	2	.899	+13
4494.756	1	.735	+21

amounts, toward the positive side. In particular I would refer to the uncertainty of the two lines at λ 4448 and λ 4495.

The direct measures made by Rowland and Jewell on each separate plate certainly possess a very high degree of accuracy, so that the relative position of the lines was determined to a precision of a few thousandths of a tenth-meter; but since each plate has a systematic error, chiefly in consequence of the application of the empirical correction, there occur, through the above-mentioned lack of uniformity in the number of plates employed, displacements in the relative position of the individual lines which may rise as high as several hundredths of a tenth-meter.

8. The relative wave-lengths of the ⊙ St. are also injuriously affected by the large variation in the number of measurements employed for the individual lines. However, the errors arising in the individual wave-lengths of the solar spectrum are for the most part rendered harmless by the extensive measurement of the whole solar spectrum which was carried out in a uniform manner, the results of which are given in the P. T. The wave-lengths of the P. T. depend upon the measurements of the photographic plates of the whole solar spectrum carried out by Jewell. In this work the newly measured lines were not merely referred to the ⊙ St. by interpolation, but a solution was made for every plate by which the ⊙ St. were also freed from their accidental errors, so that they constitute a homogeneous system with the lines newly connected to them. There accordingly exists between

the wave-lengths of the P. T. and the ⊙ St. a relation similar to that between the ⊙ St. and the P. St. (see 5). The *whole system* of the P. T. is also here to be regarded as entirely coincident with the system of the ⊙ St., but the wave-lengths of the individual lines in both systems may differ from each other by small amounts. For instance, the line D_1 appears in the P. T. with the wave-length 5896.155.

9. It appears from this statement of the history of the origin of Rowland's wave-lengths that the P. T. constitutes the definitive and most reliable form of the Rowland system. If, for instance, the question should arise which is the most correct of the four values for the wave-length of the line D_1 in the solar spectrum, viz.:

λ=5896.156 (starting value)
.157 (P. St.)
.154 (⊙ St.)
.155 (P. T.)

and which most precisely represents the Rowland system, the answer would be the value 5896.155.

10. The conclusions which were reached as to coincidence of the three systems P. St., ⊙ St., and P. T. on the basis of the history of their origin are confirmed by a direct comparison of the numerical values. The relation of the ⊙ St. to the P. St. may be seen from Table II.

The difference ⊙ St.—P. St. amounts at the maximum for a line to 0.007 tenth-meter; the sum of all these differences properly should be exactly zero; for the thirty-four lines together, however, it amounts to +0.016, whence the mean value of this difference is +0.00047 tenth-meter. Hence the two systems P. St. and ⊙ St. are sufficiently in coincidence.

11. On account of its great extent I will not print here the comparison of the system ⊙ St. and P. T., and I will limit myself to giving in Table III for intervals of 100 tenth-meters under the heading S the sum of the differences P. T.—⊙ St. In an entirely rigorous comparison S should be, at least for long stretches of spectrum, zero. The number of ⊙ St. employed is denoted by n. Several of Rowland's ⊙ St. had to be omitted in this com-

TABLE II.

P. St.	⊙ St.	⊙ St.-P. St.	P. St.	⊙ St.	⊙ St.-P. St.
4215.665	.667	+2	5397.350	.346	−4
4222.381	.381	0	5405.984	.987	+3
4376.103	.103	0	5624.254	.253	−1
			5624.764	.768	+4
4494.729	.735	+6	5826.582	.580	−2
4497.048	.041	−7	5890.184	.182	−2
4501.444	.444	0	5896.157	.154	−3
4508.460	.456	−4	5914.386	.384	−2
4690.323	.324	+1	6246.530	.530	0
4691.575	.581	+6	6318.241	.242	+1
			6322.912	.912	0
4903.484	.488	+4			
4924.110	.109	−1	6563.049	.054	+5
4924.956	.955	−1	6569.461	.461	0
5060.250	.252	+2			
5064.834	.833	−1	6750.409	.412	+3
5068.946	.946	0			
			7023.747	.747	0
5269.717	.722	+5	7027.724	.726	+2
5270.497	.495	−2	7040.056	.058	+2

parison because the measurement was made upon the center of gravity of a double line, the components of which were separately measured in the P. T. M denotes the mean error of coincidence, that is, the quotient $\frac{S}{n}$, and the last column contains the largest one of the differences P. T.−⊙ St. which occur in the particular portion of the spectrum.

Table IV contains a similar comparison for stretches of 1,000 tenth-meters.

It may be seen from the numbers of Tables III and IV that the P. T. are well related to the system of the ⊙ St., if we except the short region from λ 7000 to λ 7400, the measurement of which gave special difficulty. The difference P. T.−⊙ St. amounts in the mean to +0.00040 tenth-meter for the whole spectrum from λ 3000 to λ 7000. The errors of individual lines of the ⊙ St. exceed 0.03 tenth-meter only in isolated cases; as a rule they amount to from 0.01 to 0.02 tenth-meter.

TABLE III.

λ	*S*	*n*	*M*	Maximum
3000–3100	−0.014	21	−0.0007	+0.018
3100–3200	− 13	12	− 11	− 13
3200–3300	+ 59	10	+ 59	+ 21
3300–3400	+ 15	8	+ 19	− 12
3400–3500	− 15	16	− 9	+ 20
3500–3600	+ 50	17	+ 29	+ 18
3600–3700	− 20	29	− 7	+ 30
3700–3800	− 28	32	− 9	± 16
3800–3900	+ 77	23	+ 33	+ 20
3900–4000	+ 44	25	+ 18	+ 16
4000–4100	− 18	17	− 11	− 11
4100–4200	+ 1	9	+ 1	+ 6
4200–4300	+ 28	14	+ 20	+ 12
4300–4400	+ 33	11	+ 30	+ 10
4400–4500	− 18	13	− 14	− 18
4500–4600	− 10	9	− 11	− 3
4600–4700	− 4	12	− 3	− 7
4700–4800	− 15	5	− 30	− 12
4800–4900	+ 29	6	+ 48	+ 31
4900–5000	− 28	13	− 22	− 10
5000–5100	− 13	11	− 12	− 8
5100–5200	− 32	31	− 10	− 15
5200–5300	+ 41	28	+ 15	+ 28
5300–5400	+ 18	17	+ 11	+ 30
5400–5500	− 33	15	− 22	− 27
5500–5600	− 43	16	− 27	− 31
5600–5700	− 3	16	− 2	− 14
5700–5800	+ 8	18	+ 4	± 15
5800–5900	− 7	13	− 5	− 12
5900–6000	+ 1	13	+ 1	+ 5
6000–6100	− 19	13	− 15	− 10
6100–6200	− 26	17	− 15	− 16
6200–6300	+ 70	17	+ 41	+ 26
6300–6400	− 29	13	− 22	− 24
6400–6500	+ 90	15	+ 60	+ 29
6500–6600	+ 72	12	+ 60	+ 49
6600–6700	− 39	6	− 65	− 38
6700–6800	− 37	10	− 37	− 37
6800–6900	+ 46	35	+ 13	− 32
6900–7000	+ 36	25	+ 14	+ 24
7000–7100	+ 157	13	+ 121	+ 51
7100–7200	− 21	7	− 30	− 21
7200–7300	+ 61	12	+ 51	+ 41
7300–7400	− 14	3	− 47	− 26

TABLE IV.

λ	S	n	M	Maximum
3000–4000	+0.155	193	+ 0.0008	+0.030
4000–5000	− 2	109	0	+ 31
5000–6000	− 63	178	− 4	− 31
6000–7000	+ 164	163	+ 10	+ 49
7000–7400	+ 183	35	+ 52	+ 51
3000–7000	+0.254	643	+0.00040	+0.049

12. In Table V, I give a comparison of the systems ⊙ St. and M. St. A few lines had to be excluded here also, for which it appeared, from the remarks made by Rowland, that not precisely the same lines were measured in the solar spectrum and the arc spectrum.

TABLE V.

λ	S	n	M	Maximum
3000−3500	+0.109	29	+0.0038	+0.027
3500−4000	+ 284	80	+ 35	+ 36
4000−4500	+ 90	47	+ 19	+ 21
4500−5000	− 64	15	− 43	− 25
5000−5500	− 62	21	− 30	+ 72
5500−6000	− 64	8	− 80	− 80
3000−6000	+0.293	200	+0.0015	−0.080

An almost perfect coincidence has also been effected between the systems M. St. and ⊙ St., as is seen from the mean value holding good for the whole spectrum, $M = +0.0015$ in Table V. It has already been mentioned above under 6 that this does *not* actually occur, and it is particularly striking that the difference M. St.−⊙ St. is prevailingly positive in the stretch from λ 3000 to λ 4500; while the lines of the solar spectrum, in consequence of the greater pressure under which the absorbing strata of vapor exist in the solar atmosphere, should in general be somewhat displaced toward the red as compared with the arc lines at atmospheric pressure. Hence the difference M. St.−⊙ St. should be prevailingly negative; as may be seen from Table V, this is true, however, only between λ 4500 and λ 6000.

The conclusions drawn above are accordingly confirmed by the direct comparison of Rowland's tables of wave-length: the P. T. constitutes the most reliable form of Rowland's wave-lengths; the ⊙ St. and the P. St. coincide on the whole with the P. T., but nevertheless individual lines have large accidental errors; the M. St. similarly contain large accidental errors, and are, moreover, systematically displaced by measurable amounts as compared with the system of the P. T.

13. At this point I will also refer to another system of wave-lengths which bears the same relation to the M. St. that the P. T. bears to the ⊙ St. This is the "Normale aus dem Bogenspectrum des Eisens," which Kayser published in the year 1900.[1] Kayser's standards, which I shall briefly designate with K., are — aside from a region near λ 3400 — precisely connected to the system of the M. St., and therefore contain the constant systematic errors of the M. St., but the careful measurement of numerous plates has so far reduced the accidental errors of the separate lines in K. that the mean error of a line amounts at the most to 0.003 tenth-meter.

14. We shall certainly not be far from the truth if we assume that the accidental error of the single lines in the P. T. is about ± 0.003.[2] It is true that a direct test of the P. T. has never been made, but everyone who has occasion to employ Rowland's wave-lengths will have become convinced of their great reliability, in so far as the relative position of lines within small regions of spectrum are concerned. The conditions are, however, changed in respect to the accuracy of the relative wave-lengths as soon as widely separated portions of the spectrum are compared with each other. Attention has already been called by various individuals to the fact that there are irregularities which slowly increase in Rowland's values, as a result of which for considerable portions of the spectrum all the wave-lengths are from 0.01 to 0.02 tenth-meter too large, and in other regions are too small. Müller[3] was the first to point out the possibility

[1] *Ann. der Phys.*, (4) **3**, 195; ASTROPHYSICAL JOURNAL, **13**, 329, 1901.

[2] A proof of the correctness of this estimate follows, under 16.

[3] "Beobachtungen auf dem Gipfel des Säntis;" *Publ. des Astroph. Observatoriums zu Potsdam*, **8**, 49, 1893.

of such errors on the occasion of his making a comparison of the Potsdam system of wave-lengths with the ⊙ St. He found that the difference "Potsdam—⊙ St." had a prevailingly positive sign from λ 4900 to λ 5400, while it was negative from λ 5400 to λ 6100, and then positive again up to λ 6350. Kayser[1] expressed himself more definitely when he found that the values of several M. St. at λ 3400 are too large by from 0.02 to 0.03 tenth-meter. An entirely certain explanation as to the magnitude and the course of these errors in a part of the visual spectrum was, however, first given in the research by Fabry and Perot,[2] who determined with their interference apparatus the absolute wave-lengths of 33 lines of the solar spectrum and of 14 lines of the iron spectrum. In order to compare their results with Rowland's wave-lengths they computed for the 33 lines the quotient

$$F = \frac{\text{P. T.}}{\text{F. and P.}\odot},$$

which must be constant if Rowland's figures are free from systematic errors. The values of F show, however, a clearly expressed progression which precisely coincides in respect to sense with the results of Müller. Eberhard[3] then made a more precise comparison of the Potsdam and Rowland systems, utilizing 104 lines of the P. T., and was able to furnish another complete confirmation of Fabry and Perot.

15. There can accordingly no longer be any doubt that the wave-lengths of the P. T. are up to 0.02 unit too small from λ 4900 to λ 5370; that they are up to 0.02 unit too large between λ 5370 and λ 6050, and then again too small up to λ 6500. We may assume that similar errors will be revealed in the remaining portions of the spectrum which have not yet been checked, and the question therefore arises in what manner a correction can best be applied to the Rowland system. At the same time it would be necessary to determine the systematic

[1] *Loc. cit.*, p. 198.

[2] "Mesures de longeurs d'onde en valeur absolue," *Ann. de Chim. et de Phys.*, (7) **25**, 98; ASTROPHYSICAL JOURNAL, **15**, 270, 1902.

[3] "Systematic errors in the Wave-Lengths of the Lines of Rowland's Solar Spectrum," ASTROPHYSICAL JOURNAL, **17**, 141, 1903.

difference between the systems of the P. T. and the M. St., which have been extensively discussed above.

Fabry and Perot write, after determining the values of the reduction factor *F:* "All recent spectroscopic measurements which have been based upon Rowland's figures contain the same errors. In order to correct them, and at the same time to reduce them to the value of the wave-length of the cadmium line found by Michelson and Benoit, one has only to divide the values by *F*." I would, however, by no means recommend this procedure, for, in the first place, the systematic error above mentioned between the ⊙ St. and the M. St. is not contained in the *F*, and since most observers have used the iron spectrum for comparison and not the solar spectrum, the true value of the wave-length would not be obtained by division by *F*. Secondly, it certainly could not be recommended to alter so greatly all previously determined wave-lengths as would be necessary to pass from the Rowland system to that of Michelson. The reduction factor *F* has at this place the value 1.000034, whence it follows that all the wave-lengths in the visual spectrum would have to be diminished by about 0.2 tenth-meter if they were to be transferred to the Michelson system. This would produce great confusion.

16. I would, on the contrary, recommend that each correction of Rowland's wave-lengths should be undertaken in such a manner that his numerical values are thereby altered only by the *smallest possible* amount. This may be accomplished in the following manner. As has already been said, Fabry and Perot give the quotient $\frac{\text{P. T.}}{\text{F. and P.}} = F$ for each of the 33 solar lines they measured. The values of *F* lie between the limits 1.0000286 and 1.0000381. If we take the arithmetical mean of these thirty-three values,

$$F_0 = 1.0000340 ,$$

and multiply all the wave-lengths found by Fabry and Perot by this factor, we shall evidently obtain a system of wave-lengths which fits that of Rowland as closely as possible, but is free from its systematic errors. If we designate these errorless wave-

lengths on the Rowland system by λ, then $\lambda = (\text{F. and P.}) \cdot F_0$. I have computed the values of λ in Table VI, in which the first column contains the wave-lengths directly measured by Fabry and Perot, the second the value of λ, and the third the corresponding number in the P. T. The difference $\lambda - \text{P. T.} = C'$ given in the fourth column therefore represents the correction which must be applied to Rowland's values in order to free them of their systematic errors. The sum of all the positive values of C' is +0.178 tenth-meters, of all the negative values −0.183; a proof that the λ system coincides precisely with the P. T.

TABLE VI.

F. and P.	λ	P. T.	C'	C	$C'-C$
4643.483	4643.641	.645	− 4	− 7	+ 3
4704.960	4705.120	.131	−11	− 6	− 5
4736.800	4736.961	.963	− 2	− 5	+ 3
4783.449	4783.612	.613	− 1	− 4	+ 3
4859.758	4859.923	.928	− 5	− 1	− 4
4923.943	4924.110	.107	+ 3	+ 1	+ 2
5001.881	5002.051	.044	+ 7	+ 5	+ 2
5090.787	5090.960	.954	+ 6	+11	− 5
5123.739	5123.913	.899	+14	+14	0
5171.622	5171.798	.778	+20	+17	+ 3
5247.063	5247.241	.229	+12	+21	− 9
5247.587	5247.765	.737	+28	+21	+ 7
5339.956	5340.138	.121	+17	+13	+ 4
5345.820	5346.002	.991	+11	+11	0
5367.485	5367.667	.669	− 2	0	− 2
5409.800	5409.984	.000	−16	−11	− 5
5434.544	5434.729	.740	−11	−13	+ 2
5497.536	5497.723	.735	−12	−17	+ 5
5506.794	5506.981	.000	−19	−18	− 1
5586.778	5586.968	.991	−23	−20	− 3
5715.095	5715.289	.308	−19	−19	0
5763.004	5763.200	.218	−18	−18	0
5862.368	5862.567	.582	−15	−15	0
5934.666	5934.868	.881	−13	−11	− 2
5987.081	5987.284	.290	− 6	− 7	+ 1
6016.650	6016.855	.861	− 6	− 4	− 2
6065.506	6065.712	.709	+ 3	+ 2	+ 1
6151.639	6151.848	.834	+14	+13	+ 1
6230.746	6230.958	.943	+15	+15	0
6322.700	6322.915	.907	+ 8	+11	− 3
6335.346	6335.561	.554	+ 7	+10	− 3
6408.027	6408.245	.233	+12	+ 5	+ 7
6471.666	6471.886	.885	+ 1	+ 1	0

The accidental errors of measurement of the individual lines are still contained in the values of C'; in order to free them of

these I have graphically represented their progression by the curve reproduced in Fig. 1. From the curve we now obtain the true values C of the corrections, which are collected in Table VII. The values $C' - C$ given in the last column of Table VI correspond to the accidental errors of observation in the difference F. and P.—P. T. If we regard as equally accurate the absolute measurements of Fabry and Perot and the relative wave-lengths of the P. T., we obtain for the mean accidental error of a wave-length in the two series of measurements, $\pm$ 0.0025 tenth-

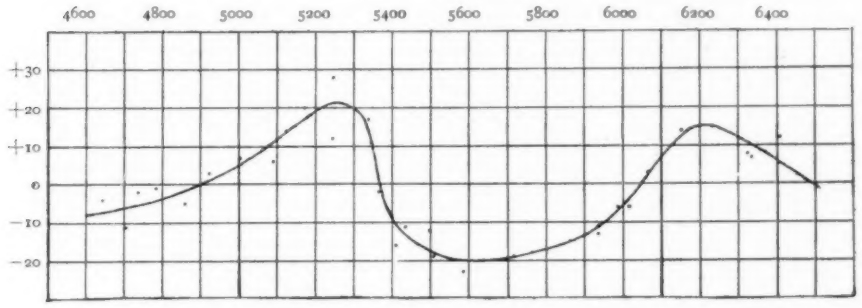


FIG. 1.

meter. The sum of all the values of $C' - C$ in Table VI is zero, whence it follows that the curve was drawn in Fig. 1 with entire accuracy.

17. It is seen that the corrections given in Table VII refer only to the stretch of the solar spectrum from λ 4600 to λ 6490 observed by Fabry and Perot, and hence there arises the necessity, on the one hand, of determining the values of C for the remaining parts of the P. T., and, on the other, of constructing a similar table of corrections for the M. St.

First, in respect to the determination of C for other portions of the solar spectrum, I made the attempt of utilizing for this purpose the plates used by Rowland himself by a new reduction. In all cases where a portion of the solar spectrum, falling within a range of Table VII, was photographed in coincidence with any other portion of the solar spectrum, the values of C for this particular new portion of the spectrum can be obtained by applying the correction from Table VII. It unfortunately

TABLE VII.

CORRECTIONS *C* OF THE P. T. FROM λ 4600 TO λ 6490.

(Unit is 0.001 tenth-meter.)

	0	1	2	3	4	5	6	7	8	9
46.....	− 8	− 8	− 8	− 7	− 7	− 7	− 7	− 7	− 7	− 6
47.....	− 6	− 6	− 6	− 5	− 5	− 5	− 5	− 4	− 4	− 4
48.....	− 4	− 3	− 3	− 2	− 2	− 2	− 1	− 1	− 1	0
49.....	0	+ 1	+ 1	+ 1	+ 2	+ 2	+ 3	+ 3	+ 4	+ 4
50.....	+ 5	+ 6	+ 6	+ 7	+ 8	+ 8	+ 9	+10	+10	+11
51.....	+12	+13	+13	+14	+15	+16	+16	+17	+18	+18
52.....	+19	+20	+20	+21	+21	+21	+21	+21	+21	+20
53.....	+20	+19	+18	+16	+13	+ 9	+ 4	− 1	− 5	− 7
54.....	− 9	−11	−12	−13	−14	−15	−15	−16	−16	−17
55.....	−18	−18	−19	−19	−19	−20	−20	−20	−20	−20
56.....	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20
57.....	−19	−19	−19	−19	−19	−19	−18	−18	−18	−18
58.....	−17	−17	−17	−16	−16	−16	−15	−15	−14	−14
59.....	−13	−13	−12	−12	−11	−10	− 9	− 9	− 8	− 7
60.....	− 6	− 5	− 4	− 2	− 1	0	+ 1	+ 3	+ 4	+ 5
61.....	+ 7	+ 8	+ 9	+10	+11	+12	+13	+14	+14	+15
62.....	+15	+15	+15	+15	+15	+14	+14	+14	+13	+13
63.....	+12	+11	+11	+10	+10	+ 9	+ 9	+ 8	+ 7	+ 7
64.....	+ 6	+ 5	+ 4	+ 4	+ 3	+ 3	+ 2	+ 1	+ 1	0

appeared that the material available for this purpose was altogether insufficient, since, for the reasons above mentioned, all measurements had to be excluded in which the wave-lengths of the solar spectrum were derived from coincidences with a metallic spectrum of another order. I was able to derive the values of the correction *C* collected in Table VIII, which are of very slight accuracy, from the few coincidences between two parts of the solar spectrum which I could utilize.

TABLE VIII.

3500	−0.004 tenth-meter
3600	− 2
3700	+ 2
3800	+ 7
3900	+ 4
4000	− 2
4100	− 7

The corrections, therefore, appear to be under 0.01 tenth-meter for this reason. We may regard as comparatively safely

determined only the stretch from λ 3890 to λ 3990, as here as many as seven plates in two different orders were used for each line. In the region of λ 4300 C appears to attain more appreciable values, but for this place, as well as for the other parts of the spectrum, there are so few measurements available that it is impossible to derive even a tolerably certain value of C from Rowland's observations.

18. The necessity is thus shown of securing new observations in order to obtain the corrections to Rowland's wave-lengths, and since the apparatus necessary for the execution of such fundamental measurements is not available to me at present, I should be glad to suggest to others the prosecution of these investigations. On account of the great importance for all spectroscopic researches of the production of as accurate and errorless fundamental system as possible, it is desirable that these researches should not be carried out at one place only, but should be independently undertaken by as many observers as possible.

There are three different problems to solve which mutually complete and check each other: *first*, the corrections C for all portions of the P. T., hence for the entire solar spectrum, should be determined; *second*, the amount of the displacement of the iron lines in the solar spectrum should be accurately determined by photographs giving the solar spectrum with an adjacent arc spectrum of iron; and *third*, a table of standard lines in the arc spectrum of iron covering the whole spectrum, and rigorously reduced to the corrected Rowland system, should be constructed.

19. If absolute measurements are made for the purpose of obtaining the corrections C, either by the interference method of Fabry and Perot or in any other way, there will always be obtained in addition to C a new determination of the reduction factor F_0. However, for the determination of C it is only necessary to make relative measurements in the solar spectrum, as by observations of coincidences with a large concave grating.

20. For the determination of the displacement of the lines of

the solar spectrum in respect to the arc lines, Jewell[1] has already contributed a very valuable series of measures, which embraces the iron spectrum from λ 3424 to λ 4495, and also includes the lines of numerous other elements. Such measurement should be repeated and extended to all regions of the spectrum. The determination of these differences, which I shall designate by *D*, the sense being solar spectrum minus arc spectrum, is at the present moment a pressing necessity in astrophysics. An exhaustive study of these displacements would not only render possible important conclusions as to the distribution of the pressure and the occurrence of the metallic vapors at different altitudes in the solar atmosphere, but would be of fundamental importance in the determination of the radial velocities of the stars. It will doubtless for a long time be the case that for all stars of the second type, which on account of the sharpness of their lines are particularly adapted for accurate determinations of velocity, the most reliable wave-lengths will be taken from the solar spectrum, since we may assume that conditions similar to those in the Sun prevail in the atmospheres of those stars. If in the computation of the velocity of such a star one should employ for the comparison spectrum the wave-lengths determined in the laboratory and referred to Rowland's M. St.—as, for instance, Kayser's iron standards—the whole amount of *D*, which Rowland did away with by empirical corrections, enters into the velocity and vitiates it. If we assume that *D* has a value of + 0.015 tenth-meter in the region of spectrum near λ 4400 chiefly employed for stars of the second type, then every velocity would be found about one kilometer greater than it should be. We should, however, commit precisely the same error if we were to employ the *same* wave-lengths for the stellar and comparison spectrum, as is always the case, for instance, when the method of coincidence measures is used.

21. The above-mentioned series of measures by Jewell is the only one which gives wave-lengths of the iron spectrum strictly referred to the system of the P. T., and I have therefore employed it in order to derive at least provisional values of the corrections

[1] *Loc. cit.*, p. 109.

which must be applied to Kayser's standard in order to make them also comparable with the P. T. Table IX contains the comparison of the lines common to the two observers.

TABLE IX.

Jewell	*K*	*k*	Jewell	*K*	*k*
3424.444	.430	+14	3815.988	.987	+ 1
3440.761	.762	− 1	3820.568	.573	− 5
3441.145	.138	+ 7	3824.584	.591	− 7
3445.308	.301	+ 7	3826.025	.028	− 3
3490.722	.721	+ 1	3827.969	.967	+ 2
3497.990	.989	+ 1	3856.515	.515	0
3536.704	.694	+10	3860.052	.054	− 2
3581.338	.348	−10	3886.415	.426	− 9
3617.934	.944	−10	3928.059	.073	−14
3618.912	.918	− 6	4022.022	.029	− 7
3622.155	.158	− 3	4045.964	.978	−14
3647.983	.997	−14	4062.597	.605	− 8
3687.597	.609	−12	4063.751	.755	− 4
3705.704	.714	−10	4071.898	.901	− 3
3720.075	.083	− 8	4199.263	.256	+ 7
3724.519	.527	− 8	4202.194	.195	− 1
3731.084	.102	−18	4222.396	.387	+ 9
3735.005	.016	−11	4271.917	.933	−16
3737.270	.278	− 8	4325.921	.941	−20
3745.691	.710	−19	4352.900	.910	−10
3748.406	.409	− 3	4369.937	.954	−17
3749.628	.634	− 6	4376.097	.104	− 7
3758.376	.381	− 5	4383.705	.724	−17
3763.932	.940	− 8	4404.911	.929	−18
3767.336	.339	− 3	4415.286	.301	−15
3788.023	.031	− 8	4447.886	.907	−21
3795.144	.149	− 5	4494.749	.755	− 6

The differences in the third column, k = Jewell − K., exhibit some rather large leaps between the individual lines, which are chiefly due to accidental errors of measurement by Jewell. I have smoothed out these figures graphically and give in Table X the values of the correction k thus found.

22. The construction of a table of standard lines of the arc spectrum of iron rigorously referred to the corrected Rowland system, which should serve as the basis for all laboratory measurements, can be accomplished in two different ways. In the first place, we may depart from the relation given above in section 16,

$$\lambda = (\text{F. and P.}) \cdot F_0 \ ;$$

that is, we may reduce to the Rowland system the wave-lengths

TABLE X.

FOR THE REDUCTION OF KAYSER'S IRON STANDARDS TO THE SYSTEM OF THE P. T.

(Unit is 0.001 tenth-meter.)

λ	k	λ	k
3400	+ 9	3950	−11
3450	+ 6	4000	−10
3500	+ 2	4050	− 7
3550	− 3	4100	− 4
3600	− 7	4150	− 1
3650	−10	4200	0
3700	−11	4250	− 2
3750	− 8	4300	− 7
3800	− 5	4350	−13
3850	− 6	4400	−16
3900	− 9	4450	−14
3950	−11	4500	−10

in the iron spectrum measured by Fabry and Perot by multiplying them with the factor $F_0 = 1.0000340$ found from their measures in the solar spectrum, and then connect to them lines in all parts of the iron spectrum by the coincidence method. Instead of the iron lines of Fabry and Perot we may employ the other metallic lines determined by interference methods by these observers as well as by Michelson and by Hamy, the wave-lengths of which, as reduced to Rowland's system, I have collected in Table XI.

The following remarks should be made in regard to this list of standard lines. Rowland's system gives the wave-lengths in air at 760 mm pressure, and at + 20° C., while Michelson's cadmium standards are referred to air at 760 mm pressure and at + 15° C. Fabry and Perot, therefore, properly ought first to reduce their wave-lengths to + 20° before comparing with the P.T. But this correction is precisely proportional to the wave-length, for the stretch from λ 4000 to λ 7000, being here

$$\lambda_{20^\circ} = 1.0000047\, \lambda_{15^\circ}.$$

This reduction factor is therefore contained in the values of F computed by Fabry and Perot, and hence also in F_0; and accordingly the wave-lengths are at the same time reduced to + 20° when they are multiplied by F_0. The values of λ in

TABLE XI.

λ	Element	Observer	λ	Element	Observer
4358.491	*Hg*	F. and P.	5460.9281	*Hg*	F. and P.
4662.5117	*Cd*	H.	5465.675	*Ag*	"
4680.297	*Zn*	F. and P.	5506.970	*Fe*	"
4722.325	*Zn*	"	5586.965	*Fe*	"
4736.946	*Fe*	"	5615.848	*Fe*	"
4800.0739	*Cd*	M.	5763.219	*Fe*	"
4810.699	*Zn*	F. and P.	5769.7946	*Hg*	"
4859.928	*Fe*	"	5782.257	*Cu*	"
5002.057	*Fe*	"	5782.356	*Cu*	"
5083.518	*Fe*	"	5790.8562	*Hg*	"
5085.9969	*Cd*	M.	5890.165	*Na*	"
5086.0754	*Cd*	H.	5896.132	*Na*	"
5105.717	*Cu*	F. and P.	6065.695	*Fe*	"
5153.426	*Cu*	"	6230.945	*Fe*	"
5154.8363	*Cd*	H.	6325.3853	*Cd*	H.
5209.258	*Ag*	F. and P.	6362.561	*Zn*	F. and P.
5218.379	*Cu*	"	6438.6911	*Cd*	M.
5233.132	*Fe*	"	6495.213	*Fe*	F. and P.
5302.501	*Fe*	"	6708.074	*Li*	"
5434.710	*Fe*	"			

Table XI are consequently rigorously referred to the corrected Rowland system (P. T. + C). The true value of the reduction factor, depending only on the absolute measurement, or upon the comparison with the standard of length, is therefore

$$\frac{1.0000340}{1.0000047} = 1.0000293 \ .$$

The large difference between the wave-lengths of the cadmium lines at λ 5086, as determined by Michelson and by Hamy, may possibly be explained by the somewhat different character of the light sources used by the two observers; as to this point, see the articles by Fabry and Perot,[1] Hamy,[2] and Bell.[3] In view of the great importance which these figures have in the construction of a new fundamental system of wave-lengths, it is nevertheless necessary that the values of Table XI should be established with entire certainty by independent series of measurements by different observers.

23. Another way for constructing a list of iron standards accurately referred to Rowland's corrected system is as follows:

[1] *Comptes Rendus*, **130**, 653, 1900; ASTROPHYSICAL JOURNAL, **16**, 36, 1902.

[2] *Comptes Rendus*, **130**, 700, 1900. [3] ASTROPHYSICAL JOURNAL, **15**, 157, 1902.

A perfectly correct system of relative wave-lengths of iron (λ') should be established, at first wholly without regard to the absolute wave-lengths, either by interference measurements or by means of coincidences obtained with a large concave grating. The wave-lengths of the same lines on the system of the P. T. is obtained by the above-mentioned (20) measures of displacements in the solar spectrum. F is obtained by the division of the two wave-lengths thus found for each line, and thereafter the reduction factor F_0 is obtained by taking the means, and then the wave-lengths of the iron lines measured are transferred to the Rowland system by means of F_0. Hence the reduction is made by the formula

$$F_0 = \frac{1}{n} \sum \frac{\text{P. T.} - D}{\lambda'} ,$$

where n is the number of lines measured, and then

$$\lambda = F_0 \lambda' .$$

24. For more convenient examination I will summarize here the relationships so far employed and the conditions which connect them:

The true Rowland system at present current is represented by the wave-lengths (P. T.) of the "Preliminary Table of Solar Spectrum Wave-Lengths."

The P. T. contain slowly progressing inequalities, for removing which the corrections C are to be applied. The wave-length of a line of the solar spectrum on the corrected Rowland system is therefore

$$\lambda_\odot = \text{P. T.} + C . \qquad (a)$$

Rowland's standards in the arc spectrum (M. St.) have been systematically vitiated by the application of empirical corrections in a manner that cannot be checked, and therefore they cannot be used as a basis for accurate measures. The system of iron standards ($K.$) of Kayser, which is accurately referred to the M. St., must therefore receive the corrections k in order to be comparable with the P. T., and the wave-length of an iron line on the corrected Rowland system is accordingly

$$\lambda_M = K. + k + C . \qquad (b)$$

There exists between $\lambda_{\odot}$ and λ_M the relation

$$\lambda_{\odot} - \lambda_M = D \ , \qquad (c)$$

wherein it must be remembered that D may change its value from line to line by leaps, and therefore cannot be interpolated, as can C and k.

It follows from equations (a) and (c) that

$$\text{P. T.} - D = \lambda_M - C \ . \qquad (d)$$

The wave-lengths of metallic lines published by Jewell give the values P. T. $- D$, and must therefore, according to (d), be corrected by the amount $+ C$, in order to furnish the correct wave-lengths:

$$\lambda_M = (\text{Jewell}) + C \ . \qquad (e)$$

For the determination of k we get from (b) and (e)

$$k = (\text{Jewell}) - K. \qquad (f)$$

If λ' are entirely correct relative wave-lengths, in order to refer them to the solar spectrum, we have either

$$F_{\circ} = \frac{1}{n} \sum \frac{\text{P. T.}}{\lambda'_{\odot}} \qquad (g)$$

$$\lambda = F_{\circ} \lambda'_{\odot} \ ,$$

whence the values of C follow from (a); or, if the λ' referred to metallic lines,

$$F_{\circ} = \frac{1}{n} \sum \frac{\text{P. T.} - D}{\lambda'_M} \qquad (h)$$

$$\lambda_M = F_{\circ} \lambda'_M \ ,$$

whence C may be obtained from (d).

If the λ' in (g) and (h) were obtained by relative measurements, the values $F_{\circ}$ have no general meaning; but if they were determined by absolute measurements—as, for instance, in the system of Michelson or Fabry and Perot—then $\frac{1}{F_{\circ}}$ is the factor for converting the corrected Rowland system into the absolute meter system; that is,

$$\lambda_{\text{abs.}} = \frac{\lambda}{F_{\circ}} \ . \qquad (i)$$

According to Michelson's determination, if the wave-lengths have been previously reduced to the same temperature of the air, the value of

$$F_{\circ} = 1.0000293 \ .$$

Use will be made of this conversion, however, only in very rare cases where the absolute values of the wave-lengths are employed. For most investigations, particularly in astrophysics, it is enough to employ the correct wave-lengths λ, which can easily be derived from all series of observations made up to the present and referred to the Rowland system, by the application of the small corrections C, D, and k.

POTSDAM, ASTROPHYSIKALISCHES OBSERVATORIUM,
June 1903.

THE PEROT-FABRY CORRECTIONS OF ROWLAND'S WAVE-LENGTHS.

By Louis Bell.

Last year in this Journal[1] I took occasion, in discussing the discrepancies between the wave-length measured by gratings and by the interferometer, to call in question the validity of the correction curve deduced by MM. Perot and Fabry for Rowland's relative wave-lengths. Their most courteous reply[2] seems to call for some comment, as it still leaves the main issue in doubt. The corrections deduced by them are actually of small magnitude, never greater than 0.03 tenth-meter and on the average less than 0.02 tenth-meter[3]—so small, in fact, that were they purely accidental, they would be negligible for most spectroscopic purposes. The serious feature of the case is that if the reality of these corrections as systematic errors is established, a grave doubt is raised as to the sufficiency of the grating for the determination of relative wave-lengths by the method of coincidences. The minute care with which Rowland's measures were made is well known, and if the method itself proves to have been faulty, spectroscopists are left entirely at sea for any practical method of establishing relative wave-lengths in ordinary spectrographic work. If an error of even 0.02 tenth-meter is due to systematic causes, errors many times greater may reasonably be expected under less favorable conditions.

For absolute measures the grating must be, as I have already shown, definitely put aside for good and sufficient cause, although I do not consider that even the beautiful work of Michelson and Benoit can yet be accepted as a final result within several times its apparent probable error. The purely metrological difficulties, well known to those who are familiar with the comparison of standards of length, are sufficient to imply some uncertainty. Michelson's value is, however, much more reliable

[1] Astrophysical Journal, **15**, 157, 1902.

[2] *Ibid.*, **16**, 36, 1902. [3] *Ibid.*, **15**, 272, 1902.

than any other, and is very properly accepted universally as the standard.

As regards relative measurements the case is different. The closeness of agreement instanced by Perot and Fabry regarding their own measures[1] can be duplicated without especial difficulty in the higher orders of a long-focus concave grating. The relative convenience of the two procedures depends on the nature of the research undertaken. Precision of setting, in methods both essentially micrometrical, is not the issue here involved. It is of fundamental importance to determine whether the grating method is or is not beset by systematic errors which, small in the case cited, may become serious. And I must here reiterate that, while systematic errors may exist in that or any other method, the evidence adduced by Perot and Fabry is insufficient to establish them.

In the first place one must recur to that extraordinary result of Hamy[2] for the wave-length of the green cadmium line. In this instance the relative values assigned by Hamy and by Michelson differ by 0.079 tenth-meter, a quantity four times greater than the differences which Perot and Fabry have sought to establish by reference to this same green line assumed as a standard. It is quite true that the experimenters used different sorts of vacuum tubes, but the observed pressure shifts of the *Cd* lines do not account for any such difference as that here found; and if they did, it would merely show such hypersensitiveness to slight changes in excitation as would indicate that the line in question is a very shifty standard. The other alternatives are a downright error in the application of interference methods, or a shifting of the apparent place of the line under differences of illumination. Until this matter is cleared up the green *Cd* line is certainly open to suspicion, and while Perot and Fabry have not heretofore had occasion to note its possible variability, they may actually have been measuring it in the case under discussion. The point is one which can be settled only by a thorough investigation.

Another source of incertitude in measures carried out by the

[1] *Ibid.*, **15**, 263, 1902. [2] *C. R.*, **130**, 489, 1900.

method of Perot and Fabry is one common to all micrometric comparisons of dark and bright lines—viz., the difficulty of treating such lines or diffraction rings just alike in making the settings. The consistency of the results does not carry proof that there is no error introduced in locating the centers of the respective objects, and that, if such an error occurs, it will remain constant when the color of the bright line or field changes. The experiments of Reese[1] and of Hasselberg[2] show very plainly that such errors occur in micrometric measures of photographic plates and that they are by no means negligible in amount. In these cases cited they partake of the nature of a personal equation which may or may not have the same sign for different observers. Whether the difference in the readings by two observers having personal equations of the same sign would be comparable in size with their common error would be a matter of chance. The smaller the absolute error, the less likely perceptible differences in it.

The general experience of spectroscopists is that it is extremely difficult to treat a bright line and a dark line just alike with the micrometer. The same difficulty extends to comparing lines of widely different appearance in general. And even supposing the personal equations of MM. Perot and Fabry to have been zero, it still remains to be shown that the dark diffraction ring as measured, having been obtained through a rather wide slit, correctly represents the wave-length of the line as it would be set upon in the grating spectrum itself. Analogy would suggest the negative, and it would be most extraordinary if the variation remained uniform in fields of different colors and intensities.

Difficulties of this sort appear in every branch of spectroscopy when dealing with quantities of the order of magnitude attacked by Perot and Fabry, and are most aggravated in comparing bright and dark lines. Even in Hasselberg's plates, which were on a large scale and uncomplicated by the question of color differences, the errors exceeded 0.01 tenth-meter.

In my previous paper I referred to a discrepancy between

[1] ASTROPHYSICAL JOURNAL, **15**, 142, 1902. [2] *Ibid.*, **15**, 208, 1902.

Perot and Fabry's correction curve and their value for the *Zn* line at λ 4810 +. The difference, as they remark, is in the direction which would be produced by pressure-shift; but Rowland's measures on the arc agree with his solar value to 0.002 tenth-meter, and the pressure shift for *Zn*, as found by Humphreys and Mohler,[1] accounts for only one-fourth of the outstanding difference of 0.02 tenth-meter. The error may be Rowland's, or Perot and Fabry's, or due to both, but it is much larger than the ostensible probable errors of either.

A far more serious source of error is the apparent neglect by Perot and Fabry of the corrections for the Earth's annual and diurnal changes of relative velocity. Perot and Fabry very carefully eliminated the velocity shift due to the Sun's rotation, but I find no record of corrections for the Earth's motion, which is almost equally important. This error affects all comparisons of solar and terrestrial sources, but of course does not appear in comparisons of solar or terrestrial sources by themselves.

Frost[2] has examined these errors and finds for the correction due to the eccentricity of the Earth's orbit a value varying from 0 to $\mp$ 0.01 tenth-meter as the Earth shifts from perihelion or aphelion to quadrature, the latter being reached in April and October. The value I here note is for the green of the spectrum. Similarly the variation with hour-angle amounts in the latitude of Paris to about $0.006 \times \sin t$ tenth-meter in the green. These quantities are quite comparable with those which Perot and Fabry have sought to evaluate, and must be reckoned with in every comparison of solar and metallic spectra, although generally, if not universally, neglected.

Any one of the sources of error which I have here noted is sufficient to account for the apparent systematic variations in Rowland's relative wave-lengths found by Perot and Fabry, and until they are eliminated, one and all, it is unsafe to assume that Rowland's relative values involve errors other than accidental. The differences found are much greater than the probable errors of reading either with the grating or the interferometer, and deserve further investigation; but they certainly should not be

[1] *Ibid.*, **3**, 114, 1896. [2] *Ibid.*, **10**, 283, 1900.

charged up to systematic errors introduced in Rowland's method of coincidences until the method used to determine them is cleared of the uncertainties which have here been noted. I do not hold Rowland's work as in the least sacrosanct, and I greatly admire the elegant method adopted by MM. Perot and Fabry; but the matter at stake is the validity of relative wave-lengths measured with the grating.

The whole discussion tends to confirm the opinion, expressed in my previous paper, that at about 0.01 tenth-meter the precision of wave-length measurements rests on a somewhat shaky foundation on account of numerous and varied small sources of error, which it is to be hoped will eventually be eliminated.

The attempt of Eberhard[1] to confirm the results of Perot and Fabry from the wave-length measurements of Müller and Kempf is interesting, but somewhat unconvincing. In Fig. 1 I have plotted the variations from Rowland's tables of the individual lines studied by Eberhard, together with some others of Müller and Kempf's lines easily identified on Rowland's map. The result is ragged in the extreme, and shows the futility of using such data to define supposed errors eight or ten times smaller than the variations in the data. The similarities between Perot and Fabry's and Müller and Kempf's curves, as shown by Eberhard, seem to be mainly due to the process of averaging. The differences are conspicuous. For instance, as between Rowland and Perot and Fabry there is practically a constant difference from λ 5900 to λ 5600. But in this particular region the difference between Rowland and Müller and Kempf is varying with great rapidity. The greatest abnormality between R. and P. and F. is at λ 5200, while between R. and M. and K. there are two regions of about equally great variation, one at λ 5300, the other at λ 6300. Add to this the wideness of the apparent variations shown by M. and K. as compared with those shown by P. and F., and I do not see how one can avoid the conclusion that the former are entirely worthless as confirmatory evidence. In Fig. 1 I have shown in addition the relation of Rowland's values to those obtained in absolute measure by Thalén.[2] These, as might

[1] *Ibid.*, **17**, 141, 1903. [2] *Nova Acta Upsala*, 1899.

be anticipated, are in vastly better accord with each other than the measures of Müller and Kempf, in which great skill was handicapped by poor gratings; but in relative values they do not agree with either M. and K. or P. and F. Thalén shows an abnormal region at about λ 5150, near that located by P. and F.,

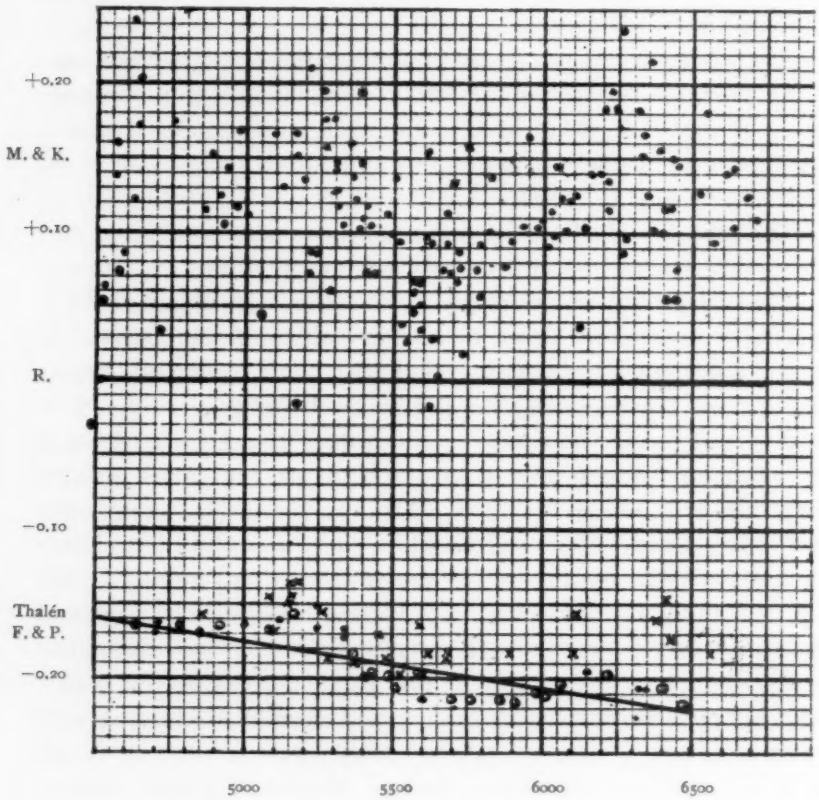


FIG. 1.

but toward the red the two sets diverge, Thalén indicating almost a constant difference from Rowland and showing no such extraordinary difference at λ 5500 as is found in M. and K. In short, Perot and Fabry, Müller and Kempf, and Thalén agree neither with Rowland nor with each other, the variations being conspicuously greater than the probable errors in each case. Rowland's values may very possibly be in error, but they obviously cannot

concurrently err by three different and considerable amounts at the same point. Considering the methods employed and the magnitudes of the supposed errors located by Perot and Fabry it is in no wise hypercritical to say that only the results of these latest experimenters can be taken seriously. I hope ere long, through the courtesy of Mr. Jewell, to have at hand a direct recomparison of certain of Rowland's lines which will confirm or reject the differences found by Perot and Fabry between the regions *circa* λ 5200 and 5700. Meanwhile these differences should be taken to heart as a lesson in the relation between probable and possible errors.

BOSTON, July 1903.

ON THE SPECTRUM AND RADIAL VELOCITY OF χ CYGNI.

By G. EBERHARD.

THE well-known variable χ *Cygni* has been observed by me at its last two appearances in 1901 and 1902 with the aid of the excellent spectrograph IV, designed by Vogel for the Potsdam photographic refractor (32.5cm). The results obtained during its appearance in 1901 have already been published in No. 3765 of the *Astronomische Nachrichten*. The observations of 1902, however, indicate departures in some respects from the star's behavior in the year preceding, and for this reason it may be

1901	G.M.T.	Plate	Observer[1]	Exposure	Slit-Width	Brightness	v from $H\gamma$	v from Fe 4308
	h m			m	mm		km	km
Aug. 2.....	9 28	IV 766	E.	150	0.025	.....	— 17.5	.....
9.....	9 10	772	L., E.	90	0.025	.....	— 17.5	.....
10.....	9 26	774	E., L.	240	0.025	$4^m.9$–$5^m.0$	— 19.9	.....
11.....	9 20	777	L., E.	30	0.025	.....	— 19.6	.....
12.....	9 4	778	E.	60	0.025	.....	— 18.1	.....
15.....	8 3	779	E., L.	55	0.015	.....	— 20.2	.....
20.....	8 2	784	L., E.	23	0.025	.....	— 21.5	.....
21.....	8 7	786	E., L.	30	0.025	4.7	— 20.5	.....
22.....	8 22	789	L., E.	30	0.020	.....	— 23.8	.....
23.....	8 10	793	E., L.	12	0.025	4.7	— 20.3	.....
24.....	10 5	794	L., E.	60	0.025	.....	— 20.6	.....
31.....	7 34	803	E., L.	60	0.025	.....	— 21.2	.....
Sept. 1.....	8 11	805	E.	38	0.025	4.9	— 20.9	.....
7.....	8 40	812	E.	60	0.025	5.0	— 21.2	— 18.6
17.....	6 59	814	E.	60	0.025	5.5 – 5.6	— 17.5	— 20.9
19.....	7 15	823	E.	60	0.025	5.6	— 22.5	— 24.2
26.....	7 36	822	E., S.	60	0.025	.....	— 20.7	— 25.3:
27.....	7 49	827	E., S.	60	0.025	5.8 – 5.9	— 19.1	.....
28.....	8 0	828	E.	60	0.025	.....	— 17.5	.....
Oct. 1.....	7 47	835	E., S.	60	0.025	6.4	— 17.2	— 16.8
3.....	8 23	838	L., S.	120	0.025	6.5 – 6.6	— 23.6	— 21.0
7.....	8 58	840	L., E.	60	0.025	6.7 – 6.8	— 18.3	.....
15.....	7 19	844	E., L.	120	0.025	7.0 – 7.2	— 19.2	— 16.9
26.....	6 15	845	E.	60	0.025	7.8 – 7.9	— 16.4:	.....
Nov. 9.....	5 40	864	L., E.	120	0.025	8.5 – 8.7	— 20.4	— 20.3
23.....	6 24	876	E., S.	180	0.025	9.0 – 9.2	— 15.7:	— 19.1:
						Mean	—19.7	—20.3

[1] Observer: E. = Eberhard, L. = Ludendorff, S. = Scholz.

well to insert here briefly, at the appropriate places, the principal results from the above-mentioned communication.

The star *χ Cygni* has a very weak absorption spectrum, on which an emission spectrum of very bright hydrogen lines and some essentially weaker metallic lines are superposed. While the bright *Hγ* line at the time of the light maximum of *χ Cygni* requires an exposure which corresponds to a star of the first type and second or third magnitude, it is necessary to expose for the continuous spectrum as long as for a star of the first type, but of about the sixth magnitude. On this account it is unfortunately impossible to obtain a good photograph of the continuous spectrum except at the time of the light maximum, and even then only on those evenings during which favorable atmospheric conditions prevail, while the bright *Hγ* line is easily photographable even when the brightness of the star is still less.

The measurement of the bright *Hγ* line and the equally bright *Fe* line at λ 4308 gave for the year 1901 the radial velocity indicated in the preceding table.

In good agreement with those figures is the radial velocity of the star obtained in 1902:

1902	G. M. T.		Plate	Observer	Exposure	Slit-Width	Brightness	v from *Hγ*
	h	m			m	mm	m	km
Sept. 22.....	7	17	IV 1158	E.	30	0.020	4.5	—16.3
23.....	8	21	1161	E., S.	240	0.025	4.5	—17.2
24.....	7	29	1162	E., S.	135	0.025	4.6	—20.4
25.....	9	23	1163	E., S.	240	0.025	4.4	—21.9
26.....	8	1	1165	E., S.	240	0.025	4.6	—21.4
28.....	7	52	1167	E.	40	0.025	.....	—17.5
29.....	6	25	1169	E., S.	15	0.025	4.4 – 4.5	—22.3[2]
30.....	6	34	1174	E., S.	20	0.015	.....	—20.7
Oct. 11.....	7	10	1176	E., S.	60	0.020	.....	—24.0
11.....	8	7	1177	E., S.	45	0 010	4.6 – 4.7	—21.7
15.....	5	38	1178	E.	40	0.015	4.8 – 5.0	—20.3
21.....	5	13	1184	E., S.	120	0.025	.....	—17.9
22.....	7	15	1195	E., S.	180	0.025	5.3	—16.8
Nov. 2.....	6	42	1210	E.	40	0.025	5.2	—24.3
7.....	6	10	1232	E., S.	30	0.020	5.3 – 5.4	—23.6
18.....	5	29	1255	E.	40	0.025	6.4	—25.9
30.....	5	28	1285	E.	50	0.025	7.5	—18.9:
Dec. 12.....	5	9	1301	E., S.	90	0.025	7.8 – 8.0	—27.0:
							Mean	—21.0

[2] *Hγ* double?

In this table it is to be noted that the estimates of the magnitude of the variable in terms of the usual comparison stars were made only incidentally, and can therefore make no claim to precision, and the given magnitudes may perhaps be uncertain by several tenths. The $H\gamma$ line presented the same appearance during both years; it was hazy toward the red, as was also $H\delta$. This caused an uncertainty in the measurement, since it was not easy, particularly in the case of fully exposed plates, always to judge in the same manner as to the place of maximum intensity which is set upon throughout the measurement. The figures given for the single plates show this clearly. I sometimes got the impression, particularly on plate 1169, that $H\gamma$ was double; but this question could not be decided with certainty in view of the comparatively slight linear extent of the spectrograms. The much fainter *Fe* line at λ 4308 could be measured only on the plates of 1901, and it was only just at the close of the observations of the next year that it was visible at all, and then it was too faint for measurement.

Nothing in the way of a law appears in the separate figures of the above tables, so that we are well justified in assuming that the radial velocity of the portions of χ *Cygni* showing the emission lines is constant and about -20 km. The comparatively large departures of the individual values from the mean are probably less to be attributed to alterations in the form of the $H\gamma$ line than to the uncertainty of the observer as to the proper place at which to make the setting.

The continuous spectrum of χ *Cygni* varies much from that of the Sun between λ 4200 and λ 4435, perhaps most closely resembling that of *a Herculis*. The intensities of many lines—as, for instance, those of *Ca* and *Va*—are wholly different from those in a star of the second type. Many of the characteristic iron lines are partially concealed by the *Fe* emission lines. In all about seventy lines could be recognized between λ 4200 and λ 4435 on the fully exposed plates, and I have made the attempt to identify these with known lines of the elements.

The presence of *Ca*, *Ti*, *Cr*, *Va*, *Fe*, and *Mg* could be established, and, in fact, practically all the principal lines of these

metals were present. Several of the absorption lines of iron were in 1901, as already stated, partially concealed by the iron emission lines; for instance, those at λ4415.29, 4383.71, 4325.94, 4308.06. But, on the contrary, no such superposition could be determined, and, indeed, the *Fe* emission lines did not appear at all until the brightness of the star was again rapidly decreasing.

There were a large number of lines, particularly of the broader ones (presumably groups), which I could not assign to any element with any degree of probability. I do not give these in detail here, since a minute knowledge of the spectrum of *χ Cygni* will not be attained until a bright star of the same, or at least of a similar, character (such as *o Ceti* at a principal maximum) has been investigated with an instrument of the greatest possible dispersion. On account of our still too limited knowledge of the continuous spectrum, there is only a small number of tolerably unobjectionable lines at our disposal for a determination of velocity. Based upon twelve and eighteen such selected lines the radial velocity of the portion of *χ Cygni* producing the continuous spectrum resulted as follows:

	1901	+2.5 km	Plate 772	1902 −1.3 km	Plate 1162
		+2.3	774	−3.3	1165
Mean		+2.4 km		−2.3 km	

I was at first of the opinion that this not particularly large difference of the values of the radial velocity was perhaps to be attributed to flexures in the apparatus during the comparatively long exposure of from two to four hours. This is, however, not very probable, since with these long exposures the *Fe* comparison spectrum was for precaution taken both at the beginning and end as well as at the middle of the exposure; moreover, the plates were made at neither very large nor very different hour angles, the middle of the exposures falling in every case near the meridian. Furthermore, if such flexures actually occur, the radial velocities of these plates, as deduced from the bright *Hγ* line, should exhibit especially large deviations from the mean values, which is not the case. Hitherto an appreciable effect of

flexure has not appeared on the plates taken with spectrograph IV, and temperature changes are excluded by the continuous careful supervision of the electric heating, so that we may assume for the present, with a high degree of probability, that the portion of χ *Cygni* producing the continuous spectrum has a variable radial velocity. Further observations will be required, however, for the certain decision of this matter, and I therefore plan to continue the spectrographic observations of χ *Cygni* during this year, particularly in respect to the above question, the solution of which is of the greatest importance for the explanation of the phenomena presented by a variable of this sort.

It is in any case quite remarkable that χ *Cygni* exhibits the same behavior as *o Ceti* in the fact that for both stars the emission spectrum is displaced toward the violet of the absorption spectrum, contrary to the manner in the case of the temporary stars. On June 1 (Plate D 115; exposure 90 m) and June 9, 1899 (D 116; exposure 150 m), two plates of χ *Cygni* were made by Dr. Ludendorff and myself with spectrograph III, which showed $H\gamma$, $H\delta$, $H\zeta$, $H\theta$, and $H\iota$ to be bright, $H\epsilon$ being lacking on account of the strong calcium absorption. $H\delta$ is by far the strongest line. A bright line having the wave-length 3905.8 also appears, and therefore coincides with the principal line at 3905.7 (Rowland) in the arc spectrum of silicon. I followed up this interesting fact and found that the line also occurred in a spectrum of *Mira Ceti* obtained by Dr. Ludendorff and myself in 1899, and that it was also doubtless measured by Vogel[1] in earlier plates of this star (λ 3906). The fact that the bright $H\beta$ line was not present, although observed by Miss Maury,[2] is to be attributed to the fact that light of this wave-length is united too far from the focus of the region ($H\gamma$ to $H\zeta$) ordinarily used, both for the photographic refractor and for spectrograph D.

On the plates of 1899, 1901, 1902 there is further present between λ 4000 and λ 4200 a series of strong brightenings, giving the impression of broad bright lines. There is a particu-

[1] "Ueber das Spectrum von *Mira Ceti*," *Sitzungsberichte der K. Akad. der Wiss. zu Berlin*, **17**, 395, 1896.

[2] *Annals of Harvard College Observatory*, **28**, I, 98.

larly strong band of this sort at λ 4138, and one lying at the side toward red of *Hδ*. Inasmuch as spectrograph IV does not permit any accurate measurements of wave-lengths in this region, I have not been able to attempt the identification of these bright bands.

In concluding I would also mention that the bright lines *Hγ*, *Hδ*, and *Fe* λ 4308 altered their intensities in different ways in 1901. From August 2 until September 19 *Hδ* was considerably brighter than *Hγ*; from October 3 to 15 *Hγ* and *Hδ* differed little from each other; on October 26 they were equal; and on November 9 and 23 *Hγ* was brighter than *Hδ*. The *Fe* line λ 4308, on the contrary, increased in brightness the fainter the star became. While it was not present on August 24 and 31 with an exposure of 60 minutes, it appeared on September 7 in an equal exposure time and remained of this intensity until about the last plate, on which it was equal to *Hγ* in brightness. The other bright *Fe* lines — for instance, λ 4402 — were only just barely visible with the exposures chosen and were in any case not measurable.

POTSDAM, June 23, 1903.

POSTSCRIPT.

(July 14, 1903.)

In *Bulletin* No. 41 of the Lick Observatory Mr. Stebbins has just published his pretty investigations of the spectrum of *o Ceti*. It is evident that my similar paper on *χ Cygni* in *A. N.* No. 3765 was unknown to him, for otherwise the highly interesting fact would not have escaped him that both stars exhibit a precisely identical behavior, both as to the spectrum and as to the variations of the spectrum; whence it is highly probable that this sort of spectrum is typical for the long-period variables of that class.

ON DOUBLE REVERSAL.

By W. J. Humphreys.

Apparently not much attention has been given to double reversal; that is, the occurrence of a narrow bright line on the dark space of a broadly reversed one. Liveing and Dewar[1] speak of having often momentarily seen, though rarely photographed, this condition on the introduction of fresh material into the arc. Kayser[2] says that he has photographed it very rarely ("nur ungemein selten"), and that he doubts the genuineness of the two cases selected from his plates to illustrate this phenomenon; a doubt well founded, as will appear presently. Jewell,[3] on the other hand, states that a certain result exhibited by double and multiple reversal, displacement of the line due to quantity of material, "is shown in a large number of cases." Still in these different papers, and elsewhere, so far as I am aware, the phenomenon is soon dismissed, and no experiments are described that help to determine just what is essential to its appearance.

Double reversal has long been known to be both persistently and well marked in the Sun's faculæ, so that there can be no doubt about its actual existence, under proper conditions; and thereby its claim to specific investigations is established.

I do not know how many photographs I have taken of arc spectra, but certainly several thousand, and of practically all known elements that can be so used. The great majority of these were secured at atmospheric pressure, but a few hundred were obtained at higher pressures, up to nearly fifteen atmospheres. The volume of the current has been multiplied more than a hundredfold, and the quantity of material in the case of several elements variously altered from mere traces to solid rods of the metal in a reasonably pure state. Still with all these changes, until a method presently to be explained was adopted, I never observed visually a single case of double reversal, and

[1] *Proceedings of the Cambridge Philosophical Society*, 4, 264.

[2] *Handbuch der Spectroscopie*, 2, 363. [3] Astrophysical Journal, 3, 95, 1896.

only a few of my plates give any evidence of it. Besides in each of these few the phenomenon is, I am convinced, entirely spurious.

An interesting case of apparent double reversal is shown in Fig. 1 of the accompanying plate. This line in the reversal of D^1 is supposed by Kayser[1] to be due to sodium, and he regards it as possibly a true double reversal, and also says[2] that it shows the displacement of the center of the reversal when a large amount of material is used from the position of the corresponding line given by a small amount of the substance.

During the course of this investigation I got what I shall call the true double reversal of the sodium D's, as shown in Fig. 4. Here both the D's are doubly reversed, and the fine lines are centrally placed. After some further experiments it was found that by mixing iron and sodium together and burning them in a common arc Fig. 1 was always obtained, but never so when the iron was left out. The conclusion therefore is, and this is supported by careful measurements, that the fine line in question is the ultra violet iron line $\lambda 2948.00$, second order, superimposed on D_1, $\lambda 5896.16$, first order.

This must not be taken as a wilful criticism of Kayser's work. All of us who have the pleasure of making investigations in this fascinating field acknowledge ourselves immeasurably indebted to him, and therefore feel it a duty as well as a privilege to make, whenever we can, even the slightest addition to or correction of his masterly treatise.

Fig. 1 seems to indicate that, while the outer layers of relatively cool sodium vapor can strongly absorb light of the wavelength given by D_1, it cannot so cut out light of double that frequency. Indeed, no theory, so far as I know, would lead us to suppose that free particles, such as fill the electric arc, could absorb vibrations other than those which they can also emit. However, that idea in this particular case was experimentally tested, as follows:

Two arcs were connected up in series, and placed, about 5 cm apart, in line with the slit of the spectroscope. The arc next the

[1] *Handbuch der Spectroscopie*, **2**, 363. [2] *Ibid.*, 365.

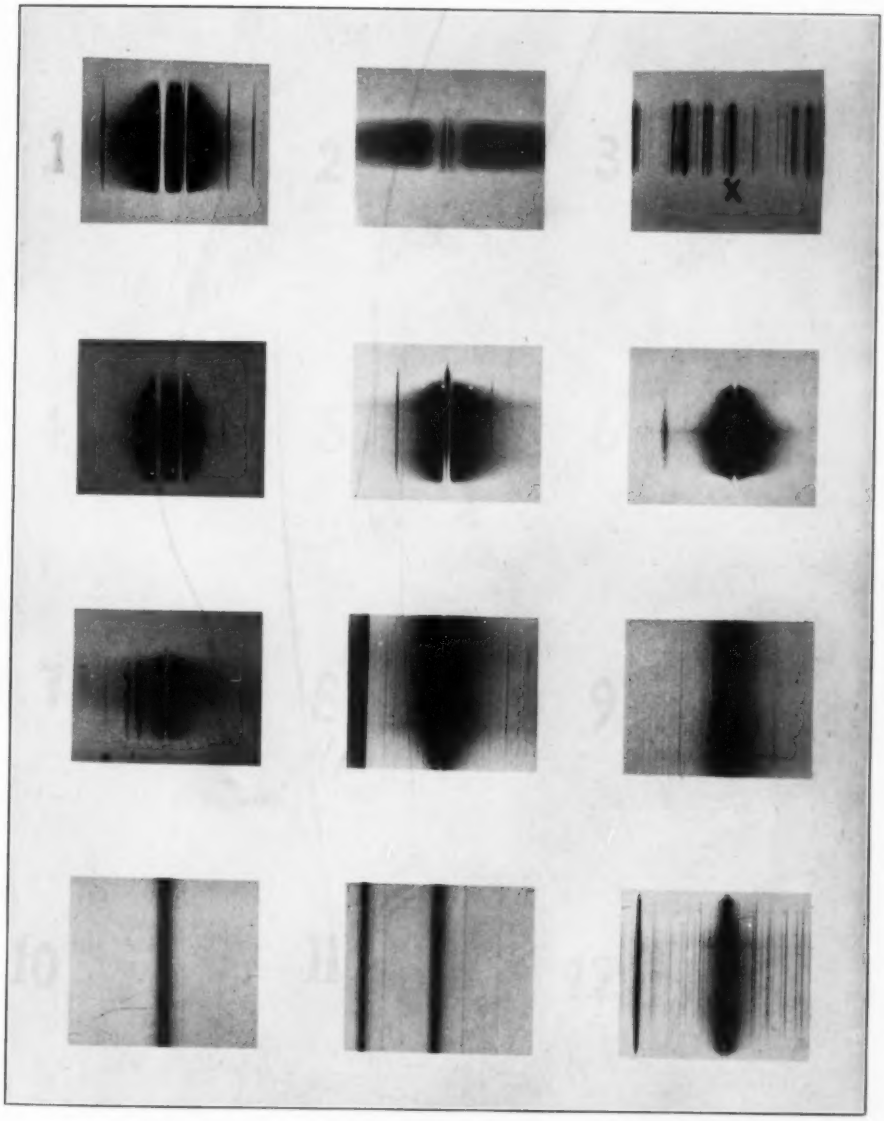
slit contained a large amount of sodium, while the one farther away had a small amount of iron. On developing the spectrogram secured with this arrangement, the fine iron line came out nicely on the reversal of D_1, and showed that its light had not been very greatly absorbed. When, instead of iron, a small amount of sodium was used in the more distant arc, no trace of the D's thus obtained could be seen on the broad reversals due to the sodium in the nearer arc. It would seem then, to borrow a musical term, that in this case the particlis that cut out one note cannot absorb its octave. Neither will it absorb the sub-octave, as is shown by mixing a trace of barium with thallium, by which the barium line $\lambda 5535.69$, first order, is superimposed on the reversal of the thallium line $\lambda 2767.97$, second order.

A somewhat different case of apparent double reversal is given by adding some iron to aluminium. Here the reversal of the aluminium line $\lambda 3092.84$ contains the iron line $\lambda 3092.87$. In this case the relatively cool vapor, in the outer parts of the arc, that cut out an aluminium radiation of a certain wave-length, either will not absorb an iron radiation of the same wave-length or else, as seems to me more likely, its absorptive power at this place is not equal to the combined corresponding emission of the two elements.

With materials free from iron, one could easily determine experimentally which of these suppositions is correct, but, as my carbons and aluminium both contain enough iron to render the results doubtful, I have not as yet undertaken it.

Occasionally two lines of the same element produce results markedly like double reversal. Thus the iron line $\lambda 2966.99$, third order, contains in its reversal the iron line $\lambda 4450.44$, second order. Also the two iron lines $\lambda 3020.70$ and $\lambda 3021.15$ both reverse in such way as to appear like a single broadly reversed line with a fine line a little to the violet of its center. But the best example I have seen of this is given, when a large amount of iron is used, by the lines $\lambda 2973.17$ and $\lambda 2973.41$. This combination, as it appears on one of my plates, is shown in Fig. 3. The fine line, nearly centrally placed in what seems to be the reversal of a single line, is, as shown by a careful determination

PLATE V.



DOUBLE REVERSAL.

of its wave-length, λ 2973.28, only the unabsorbed remnants of the red and violet sides respectively of the two reversed lines. Clearly then one side of each line is largely absorbed by the vibrating particles that produce the central parts of the other, a result in accord with the idea that in any particular case the absorption of radiant energy depends upon its wave-length and not upon its origin.

Fig. 2 illustrates probably the most common case of apparent double reversal. This line λ 3383.00 was obtained by putting a button of metallic silver in the arc. At first the arc burned violently, and most of the metal was quickly driven out. This period was followed by one of comparatively quiet action with a smaller amount of silver. The result was, therefore, a negative, produced by successive exposures, indistinguishable in appearance alone from true double reversal. In the same way I have obtained one plate that shows an apparent triple reversal of the silver lines.

As stated above, true double reversal is found in the faculæ, and it was during an attempt to explain to Professor Ormond Stone its probable origin in this case that it occurred to me to test the effect of two arcs connected in series and so placed that the light of one could reach the slit only by passing through the other. By putting a small amount of the substance to be studied in the arc nearest the slit and a large amount in the other, which was about 5 cm farther removed, the phenomenon of double reversal was always produced. On interchanging the arcs no such result appeared—only the dark reversals due to the large amount of the substance then in the nearer arc.

The following table gives a list of the lines that were thus obtained doubly reversed. All those in the visible region were repeatedly observed, and, with the exception of the lithium line, also photographed. This list, which a little care would extend, is, I trust, sufficient to show how double reversal may always be obtained; that is, by the use of two independent sources of the radiation in question, the one giving the broadly reversed line shining through the nearer source which contains a relatively small amount of the material.

The doubly reversed lines in the spectra of faculæ may therefore be interpreted as due to two practically distinct sources of light: a source deep in the Sun's atmosphere, where the material is abundant and the consequent reversals broad; and above this a more or less detached, self-luminous cloud containing a relatively small amount of the substance.

It might at first seem, if this is the explanation of double reversal, that ordinary arc spectra should often show the phenomenon, due presumably to the arc burning in two parts, one behind the other, and containing a different amount of the material. This, however, would really be two parallel arcs, and, as is well known, they will not burn that way. A split arc is therefore not a thing of any permanence, if indeed it has even a momentary existence; and thus true double reversals, as above explained, seldom, if ever, appear in arc spectra.

DOUBLY REVERSED LINES.

Element	Wave-length	Remarks	Element	Wave-length	Remarks
Ba	4554.21		*Pb*	4057.97	
"	4934.24		*Li*	6708.20	Small line complex
"	5535.69	Small line confused	*Mg*	2852.22	Fig. 7 of plate, small line also reversed
Cd	3261.17	Fig. 10 of plate			
Ca	3933.83		*Ag*	3280.80	Fig. 5 of plate, small line also reversed
"	3968.63				
"	4226.91	Fig. 8 of plate	"	3383.00	
Cu	3247.65		*Na*	5890.19	Fig. 4 of plate
"	3274.06		"	5896.16	Fig. 4 of plate
Pb	2614.26		*Sr*	4077.88	
"	2802.09		"	4215.66	
"	2823.28		"	4607.52	Fig. 9 of plate
"	2833.17		*Tl*	5350.65	Fig. 6 of plate
"	3639.71		*Sn*	3175.12	Fig. 11 of plate
"	3683.60	Fig. 12 of plate	"	3262.44	

The doubly reversed lines offer a favorable opportunity for studying the effect of quantity of material on wave-length. The lithium line λ6708.2 shows a double reversal very excellently, and even the smaller line is also often reversed. In this case the larger part of the small line is to the red of its own reversal, while when not reversed the fine line is to the blue of the center of the larger reversal.

This line was found by Michelson[1] to be a confused double, the difference in wave-length between the components being about 0.14 tenth-meter. The components are unequal in intensity, but there is no record as to which has the longer wave-length. My own observations would be fully accounted for by assuming the line to be double, as Michelson found it, and with the feebler component to the red of the heavier one.

The barium line $\lambda 5535.69$ also seemed either confused, or closely accompanied by a line due to some other element, probably the iron line $\lambda 5535.52$.

It is well known that many lines are more or less complex, some of them exceedingly so, and it may be that the brightest component, when a small amount of material is burned, does not remain so when the substance is used in quantity. At any rate, the complexity and unsymmetrical spreading of many lines make it doubtful whether the wave-length of any given component is ever changed by merely varying the amount of material producing it.

However this may be, careful and repeated measurements in both directions over my plates fail in most cases to show with certainty any displacement of the fine line from the center of the broad reversal. Even the sodium D's, *g* of calcium, the strontium line $\lambda 4607.52$, and some others, that are greatly shifted by mechanical pressure are within errors of my measurements centrally placed.

UNIVERSITY OF VIRGINIA,
August 5, 1903.

[1] *Phil. Mag.*, September 1892.

PHOTOGRAPHIC OBSERVATIONS OF BORRELLY'S COMET AND EXPLANATION OF THE PHENOMENON OF THE TAIL ON JULY 24, 1903.

By E. E. Barnard.

The quick-acting lantern lens (which is really a doublet or portrait combination, is specially suited for photographing large diffused masses of faint light in the sky. For small objects or for minute details it is, of course, unsuited because of its small scale. This kind of lens, therefore, has its limitations as well as its advantages. As an auxiliary to a larger photographic telescope for the delineation of such phenomena as the extent of comets' tails, etc., it is indispensable. The rapidity of such a lens for cometary work is well shown in the photographs made here of Borrelly's comet of this year.

The only suitable lens available at the time for photographing the comet was a small lantern lens of 1.6 in. aperture and 6.3 in. focus (see Astrophysical Journal for January 1903). With this lens attached to the 12-inch equatorial a series of photographs was obtained of the comet. These were made with the intention of accurately locating the position of the comet's tail.

Mr. R. J. Wallace, of this Observatory, becoming interested in the subject, began an independent series of photographs with the same lens at the close of my exposures, and thus covered several nights on which other work prevented my photographing the comet; for it was intended to make the set as complete as possible. By this means there were several dates on which the comet was being photographed here from dark until dawn.

In general the two pictures for any one night showed no decided difference in appearance. On the night of July 24, however, a remarkable change was shown to be taking place in the comet.

During the period of visibility of this object with the naked eye, it appeared as a bright hazy star between the second and

PLATE VI.

July 23, $15^h\ 27^m - 18^h\ 2^m$ G.M.T. July 29, $16^h\ 5^m - 18^h\ 5^m$ G.M.T.

W. E.

July 24, $17^h\ 59^m - 20^h\ 29^m$ July 24, $14^h\ 57^m - 17^h\ 34^m$

COMET *c* 1903 (BORRELLY).

third magnitudes. Feeble traces of the tail could be seen with the naked eye for some 4°. In a small telescope this could be traced for even a less distance. With every advantage in its favor—a close approach to both the Earth and Sun; above the horizon all night at a high altitude, with no moonlight to interfere; and with a head as bright as some of the "great" comets —it was decidedly disappointing so far as the naked eye was concerned. The nucleus seemed to be very inactive in the production of the ordinary phenomena of a comet's tail. The lantern-lens photographs, however, showed that the comet really had a considerable extent of tail—as much as 17°.

As stated, with the exception of the length and the accurate location of the tail, the small lens did not show much of interest until July 24, when a very remarkable and important phenomenon took place, which was almost unique in its character. Some two or three degrees back of the head the tail was apparently broken off and the outer portion shifted bodily toward the direction from which the comet was receding and in a line parallel with the remaining portion of the tail—as if some force had suddenly broken off a large section of the tail and pushed it to one side of its former position. Mr. Wallace's photograph, which was begun at the close of mine, shows that the apparent separation was taking place rapidly, as if the fragment were being left behind by the comet in its flight through space.

This singular phenomenon is not entirely unique. One of the photographs of Gale's comet of 1894 with the Willard lens showed a similar, though not so pronounced, appearance.

A photograph made on July 25 showed no traces of this peculiarity, the tail having apparently assumed its normal condition while another photograph on the 23d had shown nothing abnormal about the tail. The phenomenon was, therefore, confined to an interval of a few hours only.

The following measures were made of the photographs of July 24. "The tail" refers to the short tail attached to the head, while "the section" refers to the separate portion some 9° long, which was nearly parallel with the direction of the small tail:

PLATE I (E. E. B.).

Length of tail = 2°51′.
Distance from head to nearest end of section = 2°14′.
Distance between the axes at the point of separation = 0°12′.4.
Width of tail just back of head = 0°4′.

PLATE II (R. J. W.).

Length of tail = 4° 7′. It diffuses out beyond this.
Distance from head to nearest end of section = 2°48′.
Distance between the axes at the point of separation = 0°18′.0.
Width of tail just back of head, not so narrow — more diffused.

Following are the exposure times of the plates:

	Plate I	Plate II
Begin	$8^h\ 57^m$	$11^h\ 59^m$
End	11 34	14 20
Middle	10 15	13 14
Interval	$2^h\ 59^m$	

As will be seen, the duration of exposure was essentially the same in each case.

In the *Bulletin de la Société Astronomique de France* for August is reproduced a photograph of the comet, made by F. Quénisset, of the Observatory of Nanterre, on July 24–25 from $23^h\ 9^m$ to $0^h\ 9^m$. The scale of this photograph appears to be 5.05 times that of the lantern lens — from measures of stars on the two photographs. Assuming the above to be Paris times the following are the Greenwich times:

Begin July 24	$11^h\ 00^m$	G. M. T.
End	12 00	
Middle	11 30	

As my exposure was made at $16^h\ 15^m$ G. M. T. and Mr. Wallace's at $19^h\ 14^m$, it will be seen that Mr. Wallace's photograph was $3^h\ 0^m \pm$ later than mine, and that of M. Quénisset $4^h\ 35^m$ earlier. I have measured the distance between the head of the comet and the nearest end of the section on the Nanterre photograph, and get 1° 36′. By a combination of the times of these photographs, we get the following values of the motion of separation of the section and the head:

Nanterre and first Yerkes Observatory, - - 10′.1 hourly
First and second Yerkes Observatory, - - 10.7 hourly,

or, taking the mean of these—assuming the difference of the two results as accidental, which may not be the case—we have 10′.4 for the mean hourly motion of separation of the nearest end of the section and the head With this motion it can be shown that the separation of this section of the tail from the nucleus or the head of the comet occurred at 2^h 30^m G. M. T., July 24.

With the aid of the elements of the comet's orbit, and assuming that the direction of the tail was coincident with the prolongation of the radius vector—from which it will deviate but little at most—the hourly rate of separation was 104,000 miles, or 29 miles a second. A large portion of this was due to the comet's approach to the Sun, which amounted to 22 miles a second. The remaining 7 miles a second must, hence, be due to the motion of the tail away from the Sun, which therefore is the actual velocity of the particles of which the tail is composed.

This leads one directly to an explanation of the phenomenon observed on the photographs. The appearance in question would seem to be due to a sudden change in the direction of emission of the particles. This must have occurred between 2 and 3 o'clock, G. M. T., on July 24. If the emission had suddenly ceased altogether, then the tail would recede from the comet bodily until it dissipated in space or ceased to be luminous. Suppose, however, that, instead of stopping, the direction of emission should suddenly be shifted slightly to one side. So far as the tail at that moment was concerned, it would be the same as if the emission had ceased entirely and it would recede bodily into space; but at the same moment a new stream of particles would begin to form a new tail in the new direction, and we should have exactly the phenomenon presented by the comet on July 24. By the 25th the disconnected tail or stream of particles would have vanished by dissipation, or by ceasing to be luminous from some other cause, and the new tail would have assumed the normal appearance.

This theory may be illustrated by a jet of steam issuing from

a nozzle. If the nozzle is suddenly slightly changed in direction, the old stream will recede for a few moments before it dissipates, and a new one will follow it closely in a slightly different direction.

That the particles of the tail take a definite time to traverse its length shows that the tail may actually move as a body—a stream of small particles. Should this moving stream encounter a resisting medium of any kind, the tail would become distorted and broken, just as was shown to have occurred in the case of Brooks' comet in 1893. It is well known that swarms and streams of meteors exist within the solar system. Whether they are dense enough to produce the disturbances shown in the tails of some comets or not, it is not the purpose of this paper to say, but the explanation seems a probable one. Or there may be other currents or sources of resistance in space of which we know nothing.

There is one feature that must be taken into account in considering the motion of these particles. Previous to its free existence, the particle was moving toward the Sun with a velocity of twenty-two miles a second—as a part of the comet. When it became independent and subject to the repulsive action of the Sun, it would still approach until the repulsive force checked its speed, when for a moment it would become stationary, and then begin to recede, at first slowly, and then with rapidly increasing velocity. The hourly motion from the Yerkes Observatory plates is greater than that from the Nanterre and Yerkes Observatory plates. This would be in accordance with the above idea, except that one would expect a greater difference. The velocity derived from these photographs seems small. In many comets' tails the particles must move with a speed many times this amount.

An inspection of Mr. Wallace's photograph shows that the new tail, at its end, is growing more rapidly than the motion of the section. This would imply that some of the particles move with a much greater speed than others. By using the near end of the section, therefore, which is the only available method, one would get the velocity of only the more sluggish particles.

Following are the measures of the angles made by the tail with

the direction of the motion of the comet; that is, they are the angles the tail made with the star trails near the comet's head. It is not possible to determine this angle with great exactness, because the tail was seldom perfectly straight when the photographs were examined with a glass. The measures, therefore, represent the general direction of the tail with reference to a tangent to the apparent direction of motion of the comet.

PLATES BY B.

Date	Exposure, C. S. T.	Angle of Tail	Length	Sky
July 18.....	$10^h 24^m$ to $12^h 2^m$	42°	13°	Fair
19.....	9 22, about 20^m	39	13	Clouds
22.....	9 0 11 30	38	14	Clouds
23.....	9 27 12 2	38	13	Fair
24.....	8 57 11 34	40	15	Clouds
25.....	8 50 11 ±	36	12	Clouds
26.....	9 9	37	13	Clouds
29.....	10 5 12 5	34	8	Clouds
30.....	10 35 11	..	4	Clouds
August 16....	8 34 9 30	..	10	Thick sky

Mr. Wallace's plates have been measured in the same manner.

PLATES BY W.

Date	Exposure	Angle of Tail	Length	Sky
July 20.....	$9^h 40^m$ to $12^h 5^m$	40°	11°	
22.....	12 1 14 31	41	15	Good
23.....	12 40 14 43	38	14	
24.....	11 59 14 29	38	15	Very poor
29.....	12 30 13 40	41	7	Clouds

The long and unjustly neglected stereoscope when applied to certain astronomical subjects has become of great importance in recent years. The combination of two views of the Moon, similar with respect to phase, made on different dates, reveals its spherical form in a most beautiful manner. Dr. Max Wolf has used this instrument recently for detecting variable stars or moving asteroids on celestial photographs with great success. Two photographs of the same region of the sky with the same instrument being properly adjusted for the instrument, the asteroid or variable star will stand out conspicuously from the other stars. In 1902

he presented to the Royal Astronomical Society some stereoscopic views of Perrine's Comet of that year, in which the comet stood out in beautiful relief, apparently suspended in space before the observer. These were exhibited at the November Meeting of the Royal Astronomical Society in 1902.

In the August 1903 number of the *Bulletin* of the French Astronomical Society is published a stereoscopic picture of the present Borrelly's Comet made by F. Quénisset at Nanterre, France, which when placed in the stereoscope shows the comet in beautiful relief.

Mr. Wallace has combined one of his photographs and one of mine of this comet made on the night of July 22 for the stereoscope. The result is surprisingly beautiful. The comet appears to be suspended in space between the observer and the stars in a most realistic manner. The result is what really happens in space, but which cannot be seen in any manner except with the aid of the stereoscope. A reproduction of Mr. Wallace's beautiful combination is given here, Plate VII, with the other pictures of the comet, and when placed in a stereoscope will exhibit the comet in splendid relief.

Following are descriptions of all of the photographs of the comet obtained here:

1903, July 18 (B.).—Very slight curvature of the tail, convex side preceding. It is narrow back of the head and gradually widens a little. The axis is not symmetrical with the center of the head. There are indications of a thin tail or fragment of a tail symmetrical with the head and preceding the main tail.

July 19 (B.).—Tail faint and feeble and apparently straight.

July 20 (W.).—Tail narrow back of head, and gradually widens out considerably, symmetrical with axis.

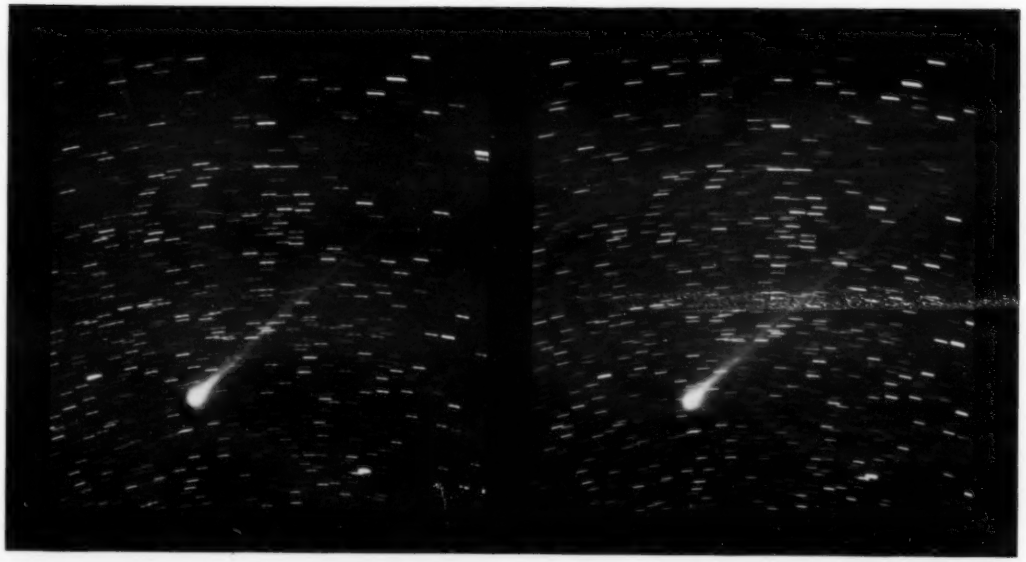
July 22 (B.).—Several strands in tail back of head, one of which is sharply defined and thread-like and is in the following side of the tail. About 6° from the head there becomes visible a faint strip 9° long, which runs parallel with the following side of the tail and distant from it 0°.2. This seems to have no connection with the head. Back of the head the tail is not so narrow as before.

July 22 (W.).—Three thread-like strands back of head. These fade out into the tail farther back. The faint strip shown on B.'s plate not visible.

July 23 (B.).—Indications of several strands from the head for some 3° to 4°. The tail bulges out slightly, preceding.

PLATE VII.

July 22, $15^h\ 0^m - 17^h\ 30^m$ G.M.T. July 22, $18^h\ 1^m - 20^h\ 31^m$ G.M.T.



COMET *c* 1903 (BORRELLY). FOR THE STEREOSCOPE.

July 23 (W.).—Shortly after leaving the head the tail is faintly double, as if a fainter portion ran along beside it following.

July 24 (B.).—The tail is very narrow back of the head, and is sharper on the following side. The section is equally sharp on both sides; the nearer end is narrow and more or less pointed.

July 24 (W.).—The main tail is narrow. Near the break it brushes out somewhat preceding. The section of tail is diffused on its preceding side, and apparently slightly double in places; the following edge of it is sharper.

July 25 (B.).—Faint and straight. No signs of the fragment of last night. The exposure was so interrupted by clouds that the utter dissipation of this fragment is not certain. If present, it must have been extremely faint.

July 26 (B.).—The tail is faint and straight, but is somewhat sinuous 3′ back of head, where it bulges out slighly, preceding.

July 29 (B.).—Slightly sinuous about 2°.2 back of head, and bulging out slightly, preceding. The tail gradually widens out. Its end is cut off by defect in negative.

July 29 (W.).—The tail is faint and apparently straight. If continued, it would cut through ϵ *Ursae Majoris*.

July 30 (B.).—Faint traces of tail for 3°.5. It seems to be straight, but is cut off by defect in negative.

August 16 (B.).—Tail extremely faint clear up to the head. It appears to be straight.

It is evident that the faint strip of tail shown on B.'s plate of July 22 is a stream of particles whose emission had ceased or changed its position some hours before.

In *Knowledge* for August is a reproduction of a photograph of the comet on July 24, made by Dr. Roberts. This shows the phenomenon exhibited on our plates for that date. Dr. Roberts has failed to give the time of this photograph, or of the others reproduced with it, and hence unfortunately the picture at present cannot be used for determining the motion of the fragment.

YERKES OBSERVATORY,
August 1903.

Minor Contributions and Notes.

AN APPLICATION OF THE CROSSLEY REFLECTOR OF THE LICK OBSERVATORY TO THE STUDY OF VERY FAINT SPECTRA.[1]

INTRODUCTION.

While engaged in photographing the brighter nebulæ with the Crossley Reflector, Professor Keeler, director of the Lick Observatory, was surprised at the relative photographic brightness of the central star in the Ring Nebula in *Lyra*, though the fact had been previously remarked by many observers. This star, which is visible only in the largest telescopes, was found to be brighter photographically than the nebula itself, which is an easy object in even a comparatively small telescope. It is true that a large faint area, such as a nebula, is more readily seen than a faint stellar point, but considering that the available telescopes magnify the Ring Nebula several hundredfold, and in effect leave the star unmagnified; that the image of the nebula photographed with the Crossley Reflector is virtually magnified but twenty-fold; and that the star photographs in about half the time required by the nebula, under good atmospheric conditions — making allowance for the physiological effect referred to, and for the proportions of the instrument, the photographic brightness of the star suggested that its spectrum contains an unduly large proportion of actinic rays. Professor Keeler also noticed that the central star in the Ring Nebula in *Cygnus* (H IV 13) behaved in the same manner. He tried to examine their spectra, both with a direct-vision spectroscope and with a prism held in the path of the rays, but in neither case was the spectrum bright enough to be seen. He therefore decided to construct a spectrograph for the study of these objects.

Such an instrument, to preserve and utilize the enormous advantages of the silver-on-glass reflecting telescope for work in the violet and ultra-violet regions, called for a design radically different from those of conventional spectrographs. It would evidently be difficult for a star near the limits of vision to be centered and kept upon a narrow slit; the method of guiding by means of a reflecting slit would not

[1] *Lick Observatory Bulletin* No. 35.

answer; and it would be important to avoid the usual losses due to a slit. The instrument as originally designed consisted, in outline, of a 50° quartz prism with circular aperture of 27 mm, placed directly in the converging beam of light from the great mirror, at a distance of 15 cm inside the focus; of a plate-holder suitably placed; and of a guiding eyepiece working on the same principle as that employed in ordinary nebular photography.

Director Keeler had thought that by placing the prism approximately at minimum deviation for the ray coinciding with the collimation axis, the confusion in the image due to the very large angle of the cone of incidental light, would be so slight as not to interfere with the qualitative purposes of the instrument; especially since the dispersion would be small—only 3 mm from λ 350 to λ 500. It should be said, however, that he had doubts as to the success of this plan, but felt that it would be well worth a trial.

The spectrograph was constructed by the Observatory instrument-maker. It was completed on the day Professor Keeler left Mount Hamilton for the last time, about a fortnight before his death.

A few weeks thereafter Dr. Campbell and I tried the spectrograph, and found that the beam of light could not be brought to a focus. On account of the approaching opposition of *Eros*, and the plans for completing, if possible, Professor Keeler's program of photographing the brighter nebulæ during the following spring, the instrument was set aside until April 1901.

Director Campbell then asked me to design such changes in the instrument as would permit the insertion of a double concave quartz lens immediately in front of the prism, to render parallel the rays incident upon the prism, and of a double convex similar lens immediately behind the prism to receive the refracted rays and form the image on the sensitive plate. The lenses were constructed by the John A. Brashear Co., from constants supplied by Professor Wadsworth. These additions to the optical train necessitated several changes in the support of the plate, in the guiding fixtures, etc. The alterations were completed by the instrument-maker on June 3, and to me was assigned the duty of testing its capabilities.

DESCRIPTION OF THE APPARATUS.

The Crossley Reflector has been described in detail by Professor Keeler.[1] Nothing need be said about it here, except that, for the sake

[1] ASTROPHYSICAL JOURNAL, 11, 325, 1900.

of completeness, its focal length is 534 cm and its clear aperture 92 cm, affording a ratio of aperture to length of 1 : 5.8.

The general features of the spectrograph are shown in Fig. 1. The tube *TT* fits into a similar tube on the side of the telescope, which holds it in position just as the plate-holder and guiding apparatus for ordinary photography are held in place. The latter tube can be moved in or out by rack and pinion to focus the plate. Since it would be

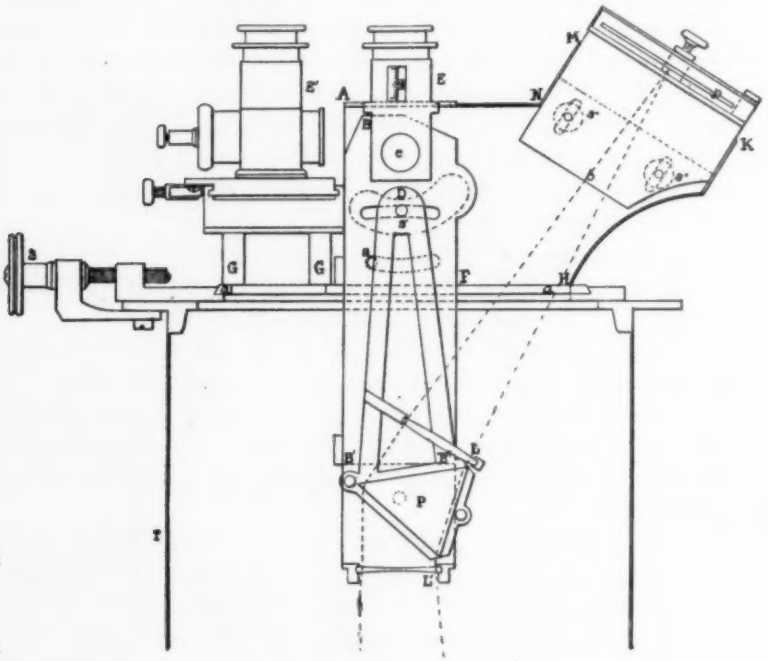


FIG. 1.

difficult to move the whole telescope to correct for any errors in following, the spectrograph is attached to the tube *TT* by two slides at right angles to each other, and the motions of these slides are controlled by two screws. In the drawing only the declination screw *S* is shown. The right-ascension screw would occupy a position in front of the middle of the apparatus, in the center of the drawing, and it is therefore omitted. The right-ascension screw has a coarse double thread to enable the observer quickly to correct the abormally large irregularities in the diurnal motion of the telescope, to which Professor Keeler's article refers at length. (The sources of much of this trouble

have been discovered and removed by Assistant Astronomer Perrine in the past year and a half, and the following in right-ascension is now much easier and better.) As the motion in declination is always small, the declination screw has a fine thread.

The base-plate *aa*, movable east and west between guides by means of the right-ascension screw, carries both the guiding eyepiece E' *GG* and the supporting framework AB' B'' *FHKMN* of the spectrograph proper. This framework is built up of sheet brass, and is about 42 mm thick. It directly supports the plate-holder attachment *bp*, the finding and focusing eyepiece *E*, and the prism-box BL'; and the prism box in turn supports the minimum deviation apparatus *DP*.

The converging beam of light from the telescope first passes through the concave lens L', which converts it into a parallel beam; then through the quartz prism *P*; and finally through the convex quartz lens *L*, which brings it to a focus on the plate *p*. The prism and convex lens are attached directly to the minimum deviation apparatus. This consists of the framework extending from *D* down to and around the prism, turning about an axis *P* near the center of the prism. It is held in any desired position by the set screw S' which works in a slot in the prism-box. A much larger slot in the spectrograph case allows the screw to be manipulated when the apparatus is in place on the telescope. The convex lens should not, theoretically, be attached to the minimum deviation apparatus, but it was the only support available for it unless extensive changes were made in the design. However, it was set with the prism in an approximately correct position, so that its axis of collimation is nearly perfect.

The concave lens L' is attached directly to the prism-box. The plate-holder attachment *bp* can be moved toward or away from the convex lens in order to bring the plate into focus. It is held in any position by four set screws s'', two on either side. These screws work in slots in the spectrograph case. The prism-box moves about the tube *C* as an axis, so that the lenses and prism can be moved far enough to the right to allow the light from a star to pass without obstruction into the focusing eyepiece *E*. It is held in position by the set screw *S*, working in a slot in the spectrograph case.

The eyepiece *E* serves to identify the object under investigation, to set the telescope so that the spectrum will fall on the center of the plate, and finally to focus the spectrograph. The eyepiece can be moved in or out, and its position be read off on the accompanying

small scale. It is held at any desired reading by a set screw (not shown in the drawing). It is so adjusted that when the spectrum has by trial been focused on the plate, the *object itself* will be in focus in the eyepiece if the prism-box be moved aside. The cross-wires in the eyepiece are illuminated by a small electric lamp placed outside the spectrograph case. It shines through the tube *C*, about which the prism-box turns.

The guiding eyepiece E' is connected with the staging through two slides working at right angles to each other, similar to the two main slides carrying the entire spectrograph. When the star under observation has been brought to the intersection of the cross-wires in the focusing eyepiece E, the eyepiece E' can be moved over an area $15' \times 45'$ in search of a suitable guiding star. When such star is found, the eyepiece is clamped to its staging, with the star on the intersection of the cross-wires. Since this staging is rigidly attached to the plate *aa* carrying the spectrograph, the spectrum will remain in correct position so long as the guiding star is kept on the cross-wires. The lamp for the guiding eyepiece is shown just below E'. The electric light used for illuminating the wires in both eyepieces is first passed through red glass, to guard against fogging the sensitive plate.

ADJUSTMENTS AND METHOD OF OBSERVATION.

The first adjustment consists in bringing the plate to the focus of the convex lens, and this is done before prism and concave lens are mounted. A positive eyepiece is fitted in the place for the plate-holder, and is so adjusted that its focus will be in the plane of the plate. The instrument is then turned to a distant object and focused by shifting the plate-box into position, whereupon the box is clamped. In this adjustment it is necessary to use blue glass between the eye and eyepiece, as the convex lens by itself is not achromatic. When the adjustment is made in this manner, the blue light is the only light which will pass through the prism in a parallel beam, but the angles of the cones of the other colors will be too small to do harm.

After the prism and concave lens have been inserted, the focusing eyepiece and minimum deviation apparatus are adjusted. For this purpose the telescope is turned to a bright star; and using the eyepiece employed in focusing the convex lens, the prism is set at minimum deviation by shifting the deviation apparatus in the usual manner, and clamping it in the correct position.

The eyepiece E is focused best by a modification of Hartmann's

method. In this case, a rectangular diaphragm is placed over the center of the concave lens with its longer dimension at right angles to the edges of the prism. When the instrument is out of focus we shall see two parallel lines, each the continuous spectrum of the star. The instrument is now focused approximately by means of the eyepiece, after which the prism is turned to the side and the eyepiece E is focused. The reading of the scale on this eyepiece gives approximately the correct position of the eyepiece. To find the accurate position of the focus, we use Hartmann's method of taking two photographs of the spectrum, one considerably inside focus, and the other considerably outside, measuring the distance between each pair of images, and from these data interpolating the true position. In this case we set the focusing eyepiece to read, first, one or two millimeters less than the approximately correct reading, and then one or two millimeters more than its correct reading. After each setting the whole spectrograph is moved until the star is in focus in this eyepiece, then the prism is turned into position and a short exposure is made. During the exposure it is necessary to guide very carefully, as any error in guiding tends to widen the two spectra. After determining the correct focus from the two plates thus obtained, the eyepiece is set in the computed position and clamped. The spectrum then and thereafter is focused merely by moving the spectrograph in or out until the object is in the focus of the eyepiece.

When the object to be photographed has been brought to the center of the field of view, the instrument is focused and a guiding star found. This should be of about the eighth magnitude, though a fainter one can be used if necessary. It is unavoidably situated so far from the axis of collimation that its image is always very much distorted. The shape of the image can be altered by moving the guiding eyepiece in or out. For some reason, the focus of the telescope changes during a long exposure, and by noting any alteration in the form of the star image a change in the focus can be detected. By using a form of image which is sensitive to slight changes, we have a very accurate method of adjusting the focus in the progress of the exposure. After adjusting the guiding eyepiece, the optical train is turned into position and the exposure begun.

In observing some of the stellar nebulæ whose positions are not accurately assigned, difficulty is often encountered in identifying the objects. If they are brighter than the eleventh magnitude, they can usually be identified by their green color; but when they are fainter

than this, recourse must be had to their spectra. Nearly all of their visual rays are concentrated in the two green nebular lines, which are so close together in this instrument that they cannot be resolved. The result is that their spectra appear simply as dots, while a star with its continuous spectra appears as a line.

The length of exposure depends entirely on the brightness of the lines. Usually the extreme ultra-violet lines require much longer exposure than the others, though there are a few cases in which they record themselves as quickly as some of the lines in the lower part of the hydrogen series of the same spectra. The faintest continuous spectrum photographed was that of a fifteenth-magnitude star, with an exposure of four hours. The spectrum was not intense, but it was abundantly strong for purposes of interpretation.

As there is no slit, sky light and moon light exert their full effects on the plate, and it is therefore not possible to photograph a faint object on a moonlight night. Several photographs of fairly bright objects have, however, been obtained within three or four days of full moon, without serious injury to the spectrum.

The plates were measured on a Zeiss comparator. With this it is possible to measure to 0.1 μ; but as only rough determinations of wave-lengths could be obtained with such a small dispersion, they were measured to 1 μ only. Even this is accurate enough to determine the wave-lengths by computation to one Ångström unit, but the probable errors were so great that the results were taken merely to the nearest $\mu\mu$. To determine the wave-lengths of unknown lines, a dispersion curve was first constructed. This curve was based upon the measure of known lines on several plates, after combining them by the method of least squares, using the Cornu-Hartmann formula. It was found that the least square determination was unnecessary, as the corrections which it gave were practically zero. This curve was plotted on such a scale that the measures could be laid off to 0.01 mm, and the wave-lengths read at a glance to 1 $\mu\mu$.

In working with a spectrograph of this kind, where no comparison spectrum is possible, all the measures must refer to some known line or lines. The interpretation of unique and unknown types of spectra would have to depend upon a comparison of the positions of the object and surrounding stars with the relative positions of the unknown spectral features and surrounding spectra on the same plate. Fortunately, in the spectra photographed thus far with this instrument, many features could always be identified; and I have in every case used the bright $H\gamma$ line as the point of reference and departure.

OBSERVATIONS.

As soon as the spectrograph was completed and adjusted, photographs were taken of the spectra of various objects to find out for what work an instrument of this kind is best adapted; and to determine its limitations. It is evident that, because of the small dispersion, it cannot as a rule be used to advantage on dark-line spectra, but some stars have been photographed with dark bands broad enough to show. This limits it very largely to bright-line spectra, though it has great value for determining the nature of very faint spectra of all kinds. Moreover, since there is no slit, the object must not be so large that the various monochromatic images will overlap too much, and this condition confines the field to objects no larger than planetary nebulæ.

Large numbers of objects having various spectral types promised to yield valuable results; but, on account of the limited time at my command, my program was confined, with the director's approval, to comparatively few objects. These included:

a) Such planetary nebulæ as were in observing position, both for purposes of comparison with results reached by observers using other instruments, and in the hope of discovering new features in the ultra-violet region. It was not expected that results already obtained in the $H\epsilon$–$H\beta$ region of bright objects, by observers using large telescopes and powerful spectroscopes, would be surpassed or even equaled, on account of the feeble dispersion of this instrument.

b) Such new stars as were in observing position.

c) The central star in the Ring Nebula in *Lyra*, and other similar stars and stellar nuclei.

d) A few Wolf-Rayet stars.

After the most of my observations were made, Professor Pickering suggested that the long-period variables be observed, to determine just when the bright hydrogen lines disappear; but lack of time prevented me from doing so.

An interesting series of observations somewhat similar to mine was made by von Gothard in 1892 (*Astronomy and Astro-Physics*, 1893, p. 51). His program included seven of the brightest planetary nebulæ, the Ring Nebula in *Lyra*, and *Nova Aurigae* after its reappearance. His telescope was a small reflector, the scale of his photographs was about the same as mine, and his results for the brighter nebulæ in the region $H\eta$–$\lambda 5007$ agree well with mine. Some of his nebulæ, however, were too large for the Crossley instrument.

Altogether, twenty-one nebular spectra were photographed by me between June and September 1901. After my departure, Mr. Joel

Stebbins, Fellow in the Lick Observatory, kindly secured for me with the same instrument some very good spectrograms of *Nova Aurigae*, *Nova Persei*, and a Wolf-Rayet star.

The general character of the different spectra is shown in Fig. 2. The scale of the original negatives was too small to permit photographic enlargements to a convenient size to be made, and they have been enlarged by drawing them to a scale of one inch to the millimeter. In the drawing, the edges of the disks appear much sharper than on the original negative.

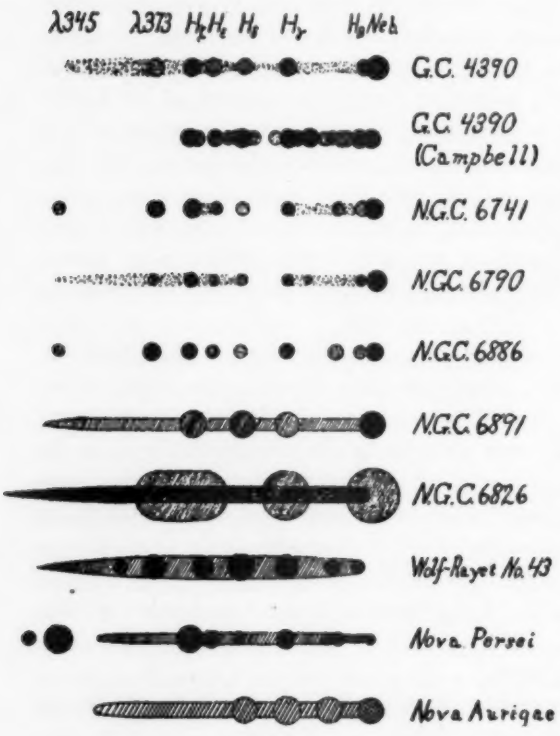


FIG. 2.

It will be noticed that in general the intensity of the continuous spectrum of the nebulæ has a minimum between $H\delta$ and $H\gamma$. This fact is confirmed by nearly all the negatives, and is too general a characteristic to be passed without notice. It seemed hardly possible that the spectrum of the nucleus, to which it was supposed that this belonged, should have an absorption band at this place, and another explanation was sought. This was found by plotting Dr. Campbell's observations of *G.C.* 4390 on the same scale, and comparing the result with the spectra obtained with the slitless spectrograph. His observations were made with a large spectroscope attached to the 36-inch refractor. A glance at the spectrum marked *G.C.* 4390 (Campbell) will show that he found the bright lines much fewer in the region where the continuous spectrum is weak in the spectrograms taken with the small instrument. His observations of *N.G.C.* 7027 give the same results. From this it seems safe to infer

that the apparently greater relative strength of my spectrograms in the $H\gamma$–$H\beta$ region is largely due to the presence of many faint overlapping bright lines, whereas, in the region $H\delta$–$H\gamma$ fewer bright lines exist. A further support of this theory is afforded by nebulæ *N.G.C.* 6826, and *N.G.C.* 6891, each of which has a stellar nucleus. In each case the spectrum of the nucleus has an almost uniform intensity throughout its entire extent.

A simple inspection of Fig. 2 will show one of the marked advantages of the reflector and quartz prism and lenses over the large refractor and glass optical train, in spectrum observations. Even in the favorable nebula *G.C.* 4390, Campbell's results stop at $H\zeta$, whereas the slitless spectrograph record extends to about λ 337.

NEBULA *N.G.C.* 6210.

This is described as very bright in Dreyer's *New General Catalogue*. Three photographs were taken with exposures of 1 minute, 5 minutes, and 30 minutes, respectively. The last is the best, the others being underexposed. The images are rather large, as the nebula is not stellar, but most of them are pretty distinct. The continuous spectrum seems to be of the kind made up largely of overlapping bright lines, with its maximum intensity in the neighborhood of $H\delta$. The following bright lines were found: principal nebular ($=\lambda$ 501 $+\lambda$ 496), $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, λ 386 and λ 373.

N.G.C. 6439.

This is a stellar nebula rated at thirteenth magnitude in the *N.G.C.* Satisfactory plates could not be obtained because there is a pretty bright star about 2′ due north of it, and the nebular spectrum appears to overlap the stellar spectrum. Three plates were made, the first with 1 hour and the other two with 2 hours' exposure. The principal nebular lines, $H\beta$, $H\gamma$, and $H\zeta$, are shown, though the last two are faint.

N.G.C. 6537.

This is a stellar nebula, and the images are small. Two plates were taken, with exposures of 1 and 1¾ hours, respectively, but both are underexposed. The latter shows the following lines: nebular, $H\beta$, λ 466, $H\gamma$, $H\delta$, $H\zeta$. There is no continuous spectrum recorded.

N.G.C. 6543.

This is a planetary nebula, marked "v B, p S" in the *N.G.C.* It has a diameter of about half a minute of arc, which is as large as can be photographed to advantage with this instrument. Two photo-

graphs of it were taken, with exposures of 15 minutes and 40 minutes, respectively. The former is the better of the two. The lines are very little brighter than the continuous spectrum; and being large they could not be measured accurately. Those identified were: nebular, + $H\beta$, $H\gamma$, and $\lambda 373$. Between $H\gamma$ and $H\beta$ the continuous spectrum is narrow, whereas beyond $H\gamma$ it is almost as wide as the nebula, as though above $H\gamma$ it were composed of overlapping bright lines. On a nebula as large as this one, it would take very few lines to cause such an appearance, the hydrogen series alone being practically sufficient. This continuous spectrum also extends above $\lambda 373$ to $\lambda 336$ as bright as it is below $\lambda 373$. It would seem that there must be other lines present in that region.

N.G.C. 6567.

This is a stellar nebula of the eleventh magnitude. But one photograph was obtained, with an exposure of 1 hour 30 minutes. The images are quite small, though not small enough to show the $H\beta$ line separated from the nebular lines. It contains the following lines: nebula, + $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, $H\zeta$, and $\lambda 373$.

The continuous spectrum recorded is of the type described above as probably due largely to overlapping bright lines. Between $H\gamma$ and $H\delta$ it is faint, and between $H\zeta$ and $\lambda 373$ it is almost invisible, but everywhere else it is bright.

G.C. 4390.

The spectrum of this nebula is shown in Fig. 2, as well as the spectrum obtained by Dr. Campbell, reduced to the scale of these spectrograms. The nebula is nearly stellar, described as "v B." Two photographs were obtained, with exposures of 10 and 15 minutes, respectively. The former is the better, although both are good.

N.G.C. 6741.

This spectrum is also shown in Fig. 2. It is a stellar nebula, but an exposure of three hours was able to bring out a continuous spectrum only from $H\beta$ to $H\gamma$ and from $H\epsilon$ to $H\zeta$. Another exposure of one hour failed to show any continuous spectrum. A new nebular line is strongly suspected at $\lambda 345$, but it is not absolutely certain.

N.G.C. 6790.

This is a stellar nebula of the 9.5 magnitude; and as it has been observed by Campbell with a larger spectroscope, little need be said about it here. Three photographs of 20 minutes', 1 hour's, and 3 hours'

exposure, respectively, were obtained. The first two show no continuous spectrum, but the third records one with a gap between $H\gamma$ and and $H\delta$. This spectrum is illustrated in Fig. 2. The continuous spectrum above $\lambda 373$ seems to be fluted, with condensation at $\lambda\lambda 363$, 356, and 352, but they are very faint and their existence is doubtful.

N.G.C. 6803.

This is a stellar nebula showing only a very faint continuous spectrum. Two photographs were obtained, one with an exposure of 1 hour, and the other with 2 hours 30 minutes. The latter shows just the faintest trace of a continuous spectrum from $H\beta$ to $H\gamma$, and from $H\delta$ to a little way beyond $\lambda 373$. The bright lines which were identified are: nebular, $H\beta$, $\lambda 468$, $\lambda 446$, $H\gamma$, $H\delta$, $H\epsilon$, $H\zeta$, $\lambda 373$, and perhaps one at $\lambda 365$, though the existence of the last is very doubtful.

N.G.C. 6807.

This is a stellar nebula without the slightest trace of a continuous spectrum. Three photographs were obtained, with exposures of 45 minutes, 57 minutes, and 3 hours, respectively. They contain: nebular, $H\beta$, $H\gamma$ $H\delta$, $H\epsilon$, and $H\zeta$ lines.

N.G.C. 6818.

This is a nebula described in the *N.G.C.* as "B, v S," but is nevertheless almost too large for this kind of work. Two photographs were obtained, with exposures of 10 minutes and 32 minutes, respectively. The former is underexposed. The spectrum consists of a pretty strong continuous spectrum extending out to $\lambda 372$, with the following bright lines: nebular, $H\beta$, $H\gamma$, $H\delta$, $\lambda 375$ and $\lambda 372$.

N.G.C. 6826.

This is described as "B, p L" in the *N.G.C.* The nebula is rather large, and contains a bright stellar nucleus which gives a continuous spectrum. A drawing of the spectrum is given in Fig. 2. Two photographs were obtained, with exposures of 15 minutes and 1 hour, respectively. The former is the better, though in both the spectrum of the nucleus is overexposed. The lines are probably: nebular, $H\beta$, $H\gamma$, $H\zeta$, and $\lambda 373$. The continuous spectrum extends to $\lambda 333$.

N.G.C. 6833.

This is one of the finest stellar nebulæ. It is the only case in which $H\beta$ was suspected visually, the image seen in this case being somewhat elongated. On the plate it is distinctly separated from the nebular

lines. But one plate was taken, with an exposure of 1 hour 55 minutes. It contains the following lines: nebular, $H\beta$, λ446, $H\gamma$, $H\delta$, $H\epsilon$, $H\zeta$, and λ373. The continuous spectrum extends to λ348, with a slight minimum of intensity between $H\gamma$ and $H\epsilon$. The variation in the brightness of the continuous spectrum is less noticeable in this case than in most of the others.

N.G.C. 6881.

This is a stellar nebula, with spectrum quite different from most of the others. Two photographs were taken, with exposures of 2 hours and 3 hours, respectively, and they show only: nebular, + $H\beta$, λ468, $H\gamma$, λλ422 and 388. There is a continuous spectrum from about λ450 to λ360, which seems to be fluted between the λ422 and λ388 lines. Still, the spectrum is too faint to allow us to decide. An exposure of at least four hours would be necessary to make sure of this point, and opportunity to secure it did not offer.

N.G.C. 6884.

This is a typical stellar nebula. The one photograph secured with exposure of 1 hour shows the following lines: nebular, $H\beta$, λ467, $H\gamma$, $H\delta$, $H\epsilon$, $H\zeta$, and λ376. There is a continuous spectrum from $H\beta$ to $H\gamma$, and from $H\epsilon$ to λ348.

N.G.C. 6886.

This is a fine stellar nebula. But one photograph was obtained, with an exposure of 1 hour. It is an excellent one, and shows the images round and small. A drawing of it is given in Fig. 2. This was the first nebula in which the new line λ345 was noticed. There is no trace of a continuous spectrum.

N.G.C. 6891.

This is a planetary nebula with a stellar nucleus. One photograph was taken with an exposure of 30 minutes. A drawing of it is given in Fig. 2.

N.G.C. 6905.

This is described as "!!, B, p S" in the *N.G.C.* It is simply a patch of nebulous matter, shading off gradually toward the edges. One photograph was taken with an exposure of 1 hour, which gives only one image of the nebula, due, probably, to the principal nebular lines.

N.G.C. 7009.

This is described as "!!!, v B" in the *N.G.C.* For so small a nebula it shows a great deal of structure. Three photographs were taken, with exposures of 5 minutes, 10 minutes, and 20 minutes, respectively. They record the nebular, $H\beta$, $H\gamma$, $H\delta$, and $H\zeta$ lines, as well as a continuous spectrum belonging to the center of the nebula. This continuous spectrum extends out to λ 345. At the $H\delta$ line it widens out to the width of the nebula, as though from there out to the ultra-violet the whole nebula gives out faint continuous light, or that there are several overlapping faint lines.

N.G.C. 7027.

This is the brightest of the stellar nebulæ photographed, being given as 8.5 magnitude in the *N.G.C.* Two photographs were taken, with exposures of 15 minutes and 30 minutes, respectively. The latter is the better of the two, although the nebular lines are so overexposed as completely to cover $H\beta$. In this nebula the λ 345 line is as bright as $H\delta$. There seems to be a very faint line at λ 337. It is very faint, but its existence is scarcely doubtful. The continuous spectrum has a minimum between $H\gamma$ and $H\epsilon$, but it does not extend quite so far as the λ 345 line.

N.G.C. 7354.

This is described as "B S" in the *N.G.C.* One photograph was taken with an exposure of 2 hours, which shows simply a single fairly bright image of the nebula, due to the nebular lines, and an exceedingly faint continuous spectrum.

NOVA PERSEI.

Several plates of *Nova Persei* were taken from September 1901, to March 1902, but the best plate was secured for me by Mr. Stebbins on October 14, with an exposure of 30 seconds. A drawing of this is given in Fig. 2. A note on this spectrum has been published by Mr. Stebbins in *Lick Observatory Bulletin* No. 8. In general the spectrum is like that of the stellar nebulæ, but resembling that of *N.G.C.* 7027 most strongly. The main difference between them is that in *Nova Persei* the brightest lines are in the ultra-violet, the green nebular lines being faint. The line suspected in *N.G.C.* 7027 at λ 337 is present here, to add to the similarity; and the line at λ 345 discovered by me in *N.G.C.* 6741 and *N.G.C.* 6886 is an exceedingly strong line in *Nova Persei.* The continuous spectrum also ends at about the same place in *N.G.C.* 7027 and the *Nova.*

NOVA AURIGAE.

Three photographs of this star were taken for my use, at the director's request, by Mr. Stebbins on September 12 and 13, 1901, with exposures of 30 minutes, 1 hour 30 minutes, and 3 hours 20 minutes, respectively. The last is the best, and is shown in Fig. 2. The visual magnitude of the star was about 13. Von Gothard[1] observed this with his objective prism on September 15, 1892, when its magnitude was 10.5. His observations are the best to compare with mine, because his dispersion was almost the same as mine. He found seven lines in this part of the spectrum, and a rather faint continuous spectrum, with a maximum brightness in the neighborhood of $H\epsilon$. Our plate made nine years later shows four lines on a nearly uniform background of continuous spectrum almost as bright as the lines themselves. Plainly the bright lines are growing relatively weaker.

NOVA CYGNI 1876.

One photograph was obtained on August 12, 1901, with an exposure of four hours. This showed that the spectrum has become continuous. At that time the *Nova* was estimated at about the fifteenth magnitude, yet the spectrum is very distinct. The plate records spectra of several stars as faint as fifteenth visual magnitude. The last published observation of this star was by Copeland and Lohse (*Copernicus*, II, 105) in 1881. At that time they surmised that the spectrum had become continuous, because they could see nothing of it, whereas, had it been a bright-line spectrum, they thought it should have been visible.

WOLF-RAYET, NO. 43.

$\alpha = 19^h\ 30.9^m$, $\delta = +30^\circ\ 19'$.

Mr. Stebbins took two photographs of this star, with exposures of 15 minutes and 60 minutes, respectively. The spectrum is shown in Fig. 2. The most noticeable difference between this and the nebulæ is the absence of the nebular lines. The continuous spectrum is nearly uniform.

RING NEBULA IN *LYRA.*

As the central star in this nebula was the principal object in mind when Professor Keeler designed the spectrograph, it was one of the first objects observed after the instrument was completed and adjusted. Three plates were taken of it, two with exposures of 30 minutes, and one with 2 hours; but the results obtained for the star were mostly

[1] *Publications A. S. P.*, 1893, 152.

negative. The rings are so large that they overlap, and only the two brightest images can be distinguished — those due to the nebular lines $+H\beta$, and to λ 373. The hydrogen lines are probably present, as the whole region between these images is darkened, probably by the overlapping images. The peculiar thing about it is that the λ 373 line is so much brighter than all of the others. Von Gothard also noticed this fact. His instrument was better adapted to this object than the Crossley Reflector is, because, having a shorter focal length, the rings were smaller; but having the same dispersion, their centers were just as far apart and consequently did not overlap so much. The only trace of the central star on these photographs is an extremely faint line, present on all three, extending from the violet edge of the green nebular ring to the red edge of the λ 373 ring. This line is too faint to be seen, except with the unaided eye. The two-hour exposure shows a dot near the middle of the λ 373 ring, but if this is due to the central star the image is a little more refrangible than λ 373. This dot is also present in the 30-minute exposure, though it is so faint that its presence would not be suspected had it not been first noticed in the long exposure.

From the fact that the spectrum of the central star is not conspicuous on these plates, it seems probable that it is almost wholly continuous, with perhaps a bright line near λ 373. The photographs taken by Professor Keeler showed that photographically the star is brighter than the nebula; and the theory that its light is spread out into a band, while the light of the nebula is concentrated in a few bright lines, seems to be the only one which explains the observed phenomena.

CONCLUSIONS.

One of the principal purposes of this investigation was to determine the efficiency of the slitless quartz spectrograph attached to the Crossley Reflector, for the photography of very faint spectra. Its power in this respect is surprisingly great. It is well illustrated in the case of *Nova Cygni*. The visual magnitude of this star was estimated by Professor Barnard in 1901 to be 15.6. My four-hour exposure, with fair following and focus, recorded its continuous spectrum in good strength, well up into the ultra-violet. The character of the spectrum could have been determined had the image been considerably less intense. This spectrum may be relatively stronger in the photographic regions than ordinary stellar spectra, though the spectra of many adjacent fifteenth-magnitude stars are recorded satisfactorily

on the same plate. It would be perfectly practicable to carry the exposures up to ten hours or more; the guiding could be more accurate, now that the principal sources of the irregularity in diurnal motion have been removed; and perhaps the more stable new telescope mounting will eliminate the present unfortunate changes in the focus during exposures. Considering these facts, I am reasonably confident that this instrument can record the continuous spectrum of the faintest star visible in the 36-inch telescope under the corresponding atmospheric conditions. Further, in the case of stellar nebulæ, etc., whose spectra contain well defined bright lines, I do not doubt that the instrument will record the principal bright lines of objects too faint to be seen in our most powerful telescope.

It is only for work on very faint spectra that this spectrograph is efficient. Its dispersive power is very low, and it should seldom be used on spectra, or on those portions of spectra, bright enough to be recorded by relatively longer exposures with instruments giving greater dispersion.

For qualitative studies of general spectral features this spectrograph is efficient on spectra of small objects, whether continuous or bright line; but for quantitative results its usefulness is limited largely to small and faint bright-line spectra.

For most of the objects observed a 60° prism, and for some of the objects two 60° prisms, would have been an improvement over the present 50° prism; requiring, of course, the reconstruction of the instrument.

For some of the stellar bright-line objects a convex lens of twice the present lens's focal length would have had an advantage in separating close lines on the photographic plate, permitting at the same time more accurate determinations of wave-lengths. This would probably alter the character of the field of the combination somewhat.

It is possible that a similar instrument on twice the linear scale, *i. e.*, with lenses and prism having 50 mm apertures—with perhaps a 60° prism—would be efficient and practicable for the objects of medium brightness on my list.

New nebular lines at λ 337 and λ 345 were discovered. These lines were later found to exist in the spectrum of *Nova Persei*, from the plate taken October 14, 1901. The nebular character of the *Nova* spectrum is thus established for the extreme ultra-violet region, as had previously been done for the other regions.

The spectrum of *Nova Cygni*, which in 1876 was of the usual "new star" type, and later changed into the nebular type, has now become continuous, with no signs of bright lines.

The bright lines in the nebular spectrum of *Nova Aurigae* are now relatively faint, and the spectrum appears to be approaching the continuous type.

These complete and astonishingly rapid changes of spectral types observed in the cases of *Nova Cygni* and *Nova Aurigae*—and likewise those observed in *Nova Normae*, *Nova Sagittarii*, *Nova Persei*, etc.—leave little doubt that the masses of these objects are small.

All the new stars of recent years should be re-observed with this spectrograph every year, to keep account of the progressive changes in their spectra. The importance of carrying out this plan can scarcely be overestimated.

The relative intensities of nebular and other bright lines, as well as of continuous spectra, are shown more accurately on the plates secured with this spectrograph than on those made with instruments absorbing the blue and violet very strongly.

The spectrum of the central star in the Ring Nebula in *Lyra* seems to be not of an unusual type, unless perhaps it contains a bright line near $\lambda 373$. It is quite possible that the star is somewhat brighter photographically than visually; at least, photographic evidence is not opposed to this theory.

The great intensity of the $\lambda 373$ ring in the Ring Nebula perhaps explains one point in nebular photography. Professor Keeler found that for most nebulæ an exposure of three hours gave the best results, whereas the best photograph of the Ring Nebula was obtained in ten minutes. While the Ring Nebula is brighter than the average bright nebula, this brief exposure of ten minutes is out of proportion to its visual brightness; but its radiations being mostly in the ultra-violet, it should have a somewhat greater photographic than visual brightness.

I wish to thank Mr. Joel Stebbins, Fellow in the Lick Observatory, for assistance in taking some of the photographs, and for making several exposures during my absence from the Observatory; and Dr. Campbell for his many suggestions during the course of the work.

HAROLD KING PALMER.

JUNE 1, 1902.

ERRATUM.

Plate III, in the September number of this JOURNAL was wrongly printed. It should be removed, and the one sent here with inserted in its place.

NOTICE.

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention will be given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

In the department of *Minor Contributions and Notes* subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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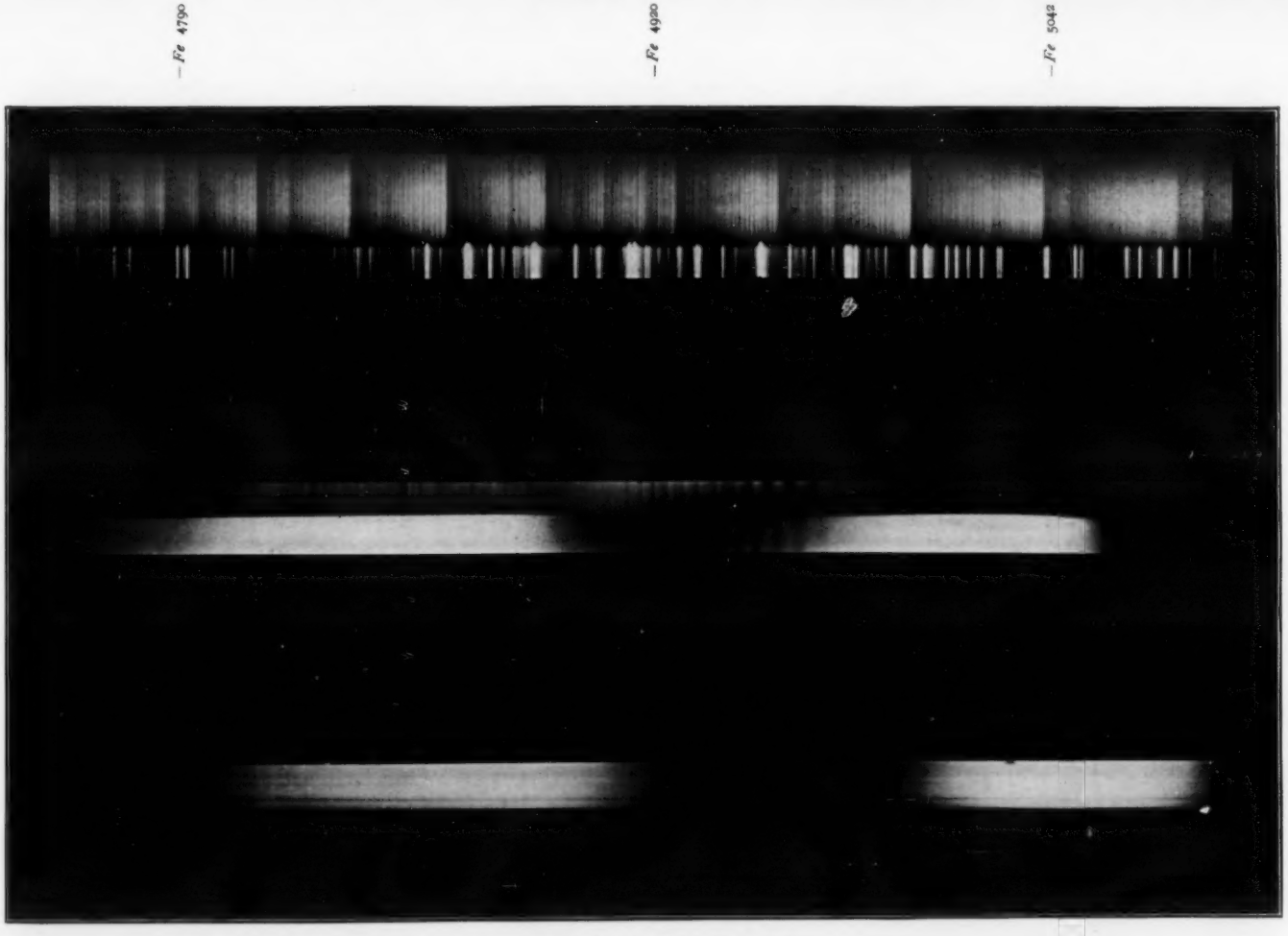
PLATE III.

PLATE III.



I (*a*). Absorption spectrum of sodium vapor. (Region from λ 4750 to λ 5100.)
(*b*). Corresponding comparison spectrum of iron.
II (*a*). Fluorescent spectrum. (The solar spectrum showing at the left half of the plate is due to diffuse light.)
(*b*). Absorption spectrum, taken with same grating.
III (*a*). Absorption spectrum, (*b*) fluorescent spectrum, showing their complementary character.